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# Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft

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## Abstract

An aircraft systems analysis was conducted to evaluate the net benefits of advanced technologies on two conceptual civil transport rotorcraft, to quantify the potential of future civil rotorcraft to become operationally viable and economically competitive, with the ultimate goal of alleviating congestion in our airways, runways and terminals.

These questions are three of many that must be resolved for the successful introduction of civil transport rotorcraft.

- *Can civil transport rotorcraft actually relieve current airport congestion and improve overall air traffic and passenger throughput at busy hub airports? What is that operational scenario?*
- *Can advanced technology make future civil rotorcraft economically competitive in scheduled passenger transport? What are those enabling technologies?*
- *What level of investment is necessary to mature the key enabling technologies?*

This study addresses the first two questions, and several others, by applying a systems analysis approach to a broad spectrum of potential advanced technologies at a conceptual level of design. The method was to identify those advanced technologies that showed the most promise and to quantify their benefits to the design, development, production, and operation of future civil rotorcraft. Adjustments are made to sizing data by subject matter experts to reflect the introduction of new technologies that offer improved performance, reduced weight, reduced maintenance, or reduced cost. This study used projected benefits from new, advanced technologies, generally based on research results, analysis, or small-scale test data. The technologies are identified, categorized and quantified in the report.

The net benefit of selected advanced technologies is quantified for two civil transport rotorcraft concepts, a Single Main Rotor Compound (SMRC) helicopter designed for 250 ktas cruise airspeed and a Civil Tilt Rotor (CTR) designed for 350 ktas cruise airspeed. A baseline design of each concept was sized for a representative civil passenger transport mission, using current technology. Individual advanced technologies are quantified and applied to resize the aircraft, thereby quantifying the net benefit of that technology to the rotorcraft. Estimates of development cost, production cost and operating and support costs are made with a commercial cost estimating program, calibrated to Boeing products with adjustments for future civil production processes. A cost metric of cash direct operating cost per available seat-mile (DOC/ASM) is used to compare the cost benefit of the technologies. The same metric is used to compare results with turboprop operating costs.

Reduced engine SFC was the most advantageous advanced technology for both rotorcraft concepts. Structural weight reduction was the second most beneficial technology, followed by advanced drive systems and then by technology for rotorcraft performance. Most of the technologies evaluated in this report should apply similarly to conventional helicopters.

The implicit assumption is that resources will become available to mature the technologies for full-scale production aircraft. That assumption is certainly the weak link in any forecast of future possibilities. The analysis serves the purpose of identifying which technologies offer the most potential benefit, and thus the ones that should receive the highest priority for continued development.

This study directly addressed the following NASA Subsonic Rotary Wing (SRW) subtopics:

- *SRW.4.8.1.3 Establish capability for rotorcraft system analysis*
- *SRW.4.8.1.4 Conduct limited technology benefit assessment on baseline rotorcraft configurations*

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## List of Symbols and Acroynms

A	Total Rotor Disk Area	LHX	Light Attack Helicopter (led to RAH-66)
AEO	All Engines Operating	JHL	Joint Heavy Lift rotorcraft
AFC	Active Flow Control	KTAS	True Airspeed, knots
AFCS	Active Flight Control System	LCC	Life Cycle Cost
APU	Auxiliary Propulsion Unit	LCT	Longitudinal Cyclic Trim
ASM	Available Seat-NM (seats*range in nm)	$L/D$	Lift to Drag Ratio
ATM	Air Traffic Management	MAC	Mean Aerodynamic Chord
BIVDS	Boeing Integrated Vehicle Design System	MDA	Multidisciplinary Analysis
BVI	Blade Vortex Interaction	MDAO	Multidisciplinary Analysis and Optimization
b	Wing Span	MDO	Multidisciplinary Optimization
CMB	Condition Based Maintenance	NAS	National Airspace System
CD	Conceptual Design	$n$	number of blades
CTR	Civil Tilt Rotor	OASPL	Over All Sound Pressure Level
$C_D$	Drag Coefficient	OEI	One Engine Inoperative
CG	Center of Gravity	OML	Outer Mold Line
$C_L$	Lift Coefficient	PD	Preliminary Design
$C_M$	Pitching Moment Coefficient	RCDA	Rotorcraft Conceptual Design and Analysis
$C_T$	Rotor Thrust Coefficient	RIA	Runway Independent Aircraft
$C_Q$	Rotor Torque Coefficient	RIO	Runway Independent Operations
DL	Disk Loading (GW/A)	RJ	Regional Jet
DOC	Direct Operating Cost	S	Wing reference area
DOE	Design Of Experiments	SFC	Specific Fuel Consumption (lb fuel/hr/SHP)
EW	Aircraft Empty Weight	SLS	Sea Level Std atmospheric condition
ECS	Environmental Control System	SMRC	Single Main Rotor Compound Helicopter
FAA	Federal Aviation Administration	SNI	Simultaneous and Non-Interfering
FATO	Final Approach and Take-Off area	SRW	Subsonic Rotary Wing
Fe	Equivalent Flat Plate Area (drag)	TLOF	Touchdown and Lift_Off area
FEM	Finite Element Model	TRL	Technology Readiness Level
$FM$	Figure of Merit	W/S	Wing loading (GW/S)
GW	Aircraft Gross Weight	V/STOL	Vertical and Short Take-off and Landing
HOG	Hover Out-of-Ground Effect	$\sigma$	rotor solidity (blade area / disk area)
HUMS	Health & Usage Monitoring System	$\mu$	advance ratio, flight speed / rotor tip speed
IVHM	Integrated Vehicle Health Management		
ISA	International Standard Atmosphere		
JVX	Joint Vertical Assault (led to MV-22)		

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# 1. Introduction

This aircraft systems analysis evaluates the benefits of advanced technology to civil rotorcraft in terms of size, weight, performance and cost. The overall objective was to identify those advanced technologies which offer high payoff to the future of safe, efficient, cost-effective VTOL civil transport rotorcraft. The method was to identify those advanced technologies that showed the most promise and to quantify their benefits to the design, development, production, and operation of future civil rotorcraft.

Conceptual design analysis does not address details of structural elements, such as the ply lay-up of composite material for a wing. It relies on well established trends of data from many previous production aircraft to estimate the component weights of new rotorcraft, based on physical dimensions, overall weight and structural and performance requirements. Engine and rotor performance are modeled with tri-variant tables of data to capture the physics of the problem. Each segment of the mission is modeled to calculate the mission fuel required. A computer analysis calculates aircraft size, weight and fuel, and iterates to convergence on an aircraft that can perform the mission. Adjustments are made to the tables and trend data by subject matter experts to reflect the introduction of new technologies that offer improved performance, reduced weight, reduced maintenance, or reduced cost. This was performed with Boeing's Rotorcraft Conceptual Design and Analysis (RCDA) integrated tool suite, including estimated Development, Production and Operating & Support costs.

Boeing applied technical expertise from many disciplines to assess the effects of advanced technologies on current and emergent vertical lift aircraft concepts. The study surveyed and evaluated many emerging technologies, including rotor and airframe performance benefits, advanced structures, advanced propulsion and advanced drive systems. Performance and weight benefits of these advanced technologies were quantified, ranked, and then incrementally applied to the conceptual design of two rotorcraft types, a civil tilt rotor (CTR) and a single main rotor compound (SMRC) helicopter, covering a speed range from 250 ktas to 400 ktas. Several metrics were used in the final analysis, including aircraft empty weight, fuel usage, and Direct Operating Cost / Available Seat-NM (DOC/ASM).

The relative importance of the three components of cost (development, production, and support) can determine the design choice in the world of military aircraft. Military aircraft require very advanced, cutting-edge technology for combat effectiveness and survivability against the ever increasing sophistication of military threats. Production costs limit the number of units that can be procured within congressional budgets. Protracted development time and overrun development costs have resulted in the termination of several aircraft programs. Military procurement decisions have historically given little attention to operating costs, but requirements for more affordable maintenance cost have become commonplace requirements in the past 15-20 years, e.g. J VX, LHX, and JHL. It must be noted here that even maintenance cost pales in comparison to the cost of fuel with high utilization rates of civil operations.

Commercial aircraft operators focus on annual fleet operating costs, generally dominated by fuel costs, with one eye on future operating costs with high utilization. So the primary metric for this study of civil rotorcraft is Direct Operating Cost per Available Seat-Mile (DOC/ASM), which must be less than the revenue per seat-mile (RASM) of commercial aircraft operators, for profitable operations.

The challenge for aircraft manufacturers is to develop, certify and produce civil transport aircraft that beat the competition in price and/or performance, e.g. DOC/ASM, and provide an aircraft where the RASM is greater than the DOC/ASM.

## 1.1. Approach

The following steps were performed in the order presented to arrive at quantitative assessments of the potential benefits of advanced technologies to civil transport rotorcraft.

- Identify operational possibilities that promote rotorcraft effectiveness in a civil transport environment.
- Define rational civil passenger transport missions for each rotorcraft concept.
- Prepare cost estimating models for each concept, applying Boeing Lean practices for civil rotorcraft development and production.
- Determine the best values for primary configuration attributes (e.g. wing loading, disk loading, cruise altitude)
- Establish baseline designs and cost estimates for each concept using current technology.
- Assess emerging technologies and operational scenarios that can enhance civil rotorcraft operations.
- Identify the most valuable technical areas through a sensitivity analysis on the baseline designs.
- Survey advanced technologies, quantify and rank them. Select the most promising.
- Re-size the baseline designs by applying the selected advanced technologies, separately and as groups. Quantify relative cost benefits by comparison to the baseline costs.

Examples of advanced technologies for civil rotorcraft include: variable-speed drive systems, active rotor control, active flow control, lightweight structure and drive system components, reduced rotor rpm in cruise, and advanced rotor designs. Favorable operational factors for civil rotorcraft are also essential to the successful introduction of civil rotorcraft to the National Airspace System (NAS). The focus is on safety, effectiveness, and the ability to relieve terminal congestion and enhance public acceptance. These factors include: all-weather operations; pilot displays to reduce workload and improve situational awareness; reduced external noise and internal cabin noise; and passenger comfort.

A robust cost estimating procedure was identified at the beginning of the study as important to the validity of the results. A procedure was selected to avoid company bias and to be independent of existing government-developed cost estimating programs. Boeing selected Price Systems' Cost Estimating program (PRICE) as a strong, generic off-the-shelf program with a substantial built-in database that assists the parametric cost analyst to set up cost models. Boeing has previous experience using PRICE and their excellent product support were also determining factors. PRICE estimates development costs, production costs, and operating and support (O&S) costs. It was integrated as a module within Boeing's integrated tool suite providing automatic cost estimating with every rotorcraft sizing case.

The system analysis approach identifies the relative contributions of advanced technologies to civil rotorcraft development, production, and operation. The sensitivity of rotorcraft configurations to the different technologies are quantified and documented. This aircraft systems analysis method quantifies the net benefits and cost derived from the technologies. "Net" benefit in this study refers to technology's effect on the whole aircraft, including performance, weight and cost, as opposed to the effect of technology on a component weight.

## 1.2. Project Scope

Many candidate rotorcraft concepts were considered for this study from the field of possibilities shown in Figure 1. Two rotorcraft configurations were selected: a Civil Tilt Rotor (CTR) concept and a Single Main Rotor Compound (SMRC) helicopter concept. The importance of the selected configurations was

not to prove their worth as concepts, but to act as the baseline configurations during evaluations of the cost and benefit of advanced technologies on civil passenger transport rotorcraft.

The net benefits of advanced technologies on aircraft development cost, production cost and O&S cost are a consequence of rotorcraft down-sizing and reduced weight from the advanced technologies. The cost benefits are presented as relative values to the baseline configurations, consistent with the comparative nature and objective of the study. These relative values allow each technology benefit to be compared with others, and the relative benefit of combined technologies to the whole aircraft. It also identifies how those benefits differ between the SMRC high-speed helicopter and the higher-speed CTR.



**Figure 1. Candidate Rotorcraft Concepts**

### 1.3. Success Criteria

A short list of criteria for a successful civil passenger transport rotorcraft were formulated during the study, focusing on the marriage of essential rotorcraft attributes and acceptance by passengers and the community. These are necessary criteria for the rotorcraft vehicle, but are not sufficient criteria for successful implementation of rotorcraft into the National Airspace System (NAS).

A supportive infrastructure and environment must also exist. That is, the FAA and local authorities must recognize the potential offered by VTOL aircraft and be prepared to develop the necessary infrastructure of V/STOL operating strips and terminals, mostly at existing major airports. Potential airline operators must recognize the economic advantage of being able to operate additional conventional fixed wing aircraft from the new runway slots and gates that become available by an infusion of civil transport rotorcraft.

This short list of success criteria is considered self-explanatory to those in the rotary wing world. The terms “Lower”, “Improved”, “Higher”, and “Increased” are relative to existing civil rotorcraft with fewer than 30 passenger seats and low mission range.

#### A. Economically competitive (\$DOC/ASM)

- Lower empty weight (EW)
- Lower maintenance man-hours per flight hour (MMH/FH)

- Improved air vehicle and engine performance
- B. Increased Availability/Reliability
  - Higher MTBO, On-condition Replacement
  - Availability consistent with high-utilization in a commercial application
- C. Passenger Acceptance/Comfort
  - Low vibration
  - Moderate Internal Noise Levels
- D. Operational flexibility
  - Runway independent operation
  - Avionics support situational awareness for non-linear approach/departure paths
- E. Satisfy all FAA certification requirements and local noise ordinances



## **2. Operational Concept for Civil Transport Rotorcraft**

### **2.1. Background**

National Airspace System (NAS) traffic system metrics are: Safety, Predictability, Flexibility, Capacity and Efficiency. The question for this study is: *How can future civil rotorcraft offer an operationally viable and cost competitive supplement to fixed wing aircraft that will meet growing passenger demand, reduce airport runway and terminal congestion, and provide increased safety?*

This section addresses the past and current operational concepts that pave the way for future rotorcraft operating independently of fixed wing operations. A thorough assessment and background for this operational concept was prepared by Ryan Wilkins of Boeing under this contract<sup>1</sup>. It is available in its entirety from Boeing on request. The following brief includes excerpts from that document.

#### **2.1.1. Increased Passenger Demand**

U.S. and international airspace delays and problems continue to multiply. Passenger demand has grown at an unprecedented rate, faster than expected, partly due to reduced airfares of several new, small operations such as Ryanair and JetBlue. Since 2002 after 9/11, through 2006, the annual system passenger emplacements increased by 17.6%, from 612,877,000 to 744,586,000<sup>2</sup>. This far exceeds the expected demand increase of 4% to a high of 6-8% expected in 2000, prior to Sept 11, 2001.

#### **2.1.2. Facility Capacity Delay**

According to the latest U.S. Department of Transportation survey, just 71.1 percent of the nation's flights arrived on time in August, 2007. That's almost 5 percentage points down from August 2006, continuing the yearlong decline in airline efficiency. Cumulative, year-to-date on-time airline performance is the worst it has been in 13 years. In August 2007, 159 flights spent more than three hours on the nation's runways waiting to takeoff. Three flights sat on the tarmac for more than five hours.<sup>3</sup>

As passenger demands increase so does the demand for air carrier access to already constrained terminal airspace. Departures increased from 9,187,000 to 11,268,000, or an increase 18.46%. The problem is not so much the airspace as it is the terminal facility, specifically at the runway. Of the 31 FAA benchmarked airports related to capacity and delay, 15 have recorded delay increases of 20% or more, with 8 of them contained within the "Golden Triangle" (Chicago – Boston – Atlanta) of maximum air traffic<sup>4</sup>. As of October 3, 2007 the Department of Transportation's Bureau of Transportation Statistics reported that the nation's 20 largest carriers reported an on-time arrival rate of 71.1 percent in August, down from 75.8 percent a year ago. The increase in delay, and a corresponding reduction in through put and capacity, can be blamed on the increased operations of smaller aircraft such as Regional Jets that take up the same runway occupancy time and terminal space as larger capacity aircraft. According to the FAA, outdated air traffic control technology, bad weather and increasing passenger traffic, all contribute to

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<sup>1</sup> Wilkins, Ryan, "Use of ESTOL and/or V/STOL Aircraft in the Next-generation National Airspace System: Concept of Operations", Boeing Rotorcraft White Paper, Oct, 2007

<sup>2</sup> Annual Traffic and Ops: U.S. Airlines, Air Transport Association, Economics and Energy, <http://www.airlines.org/economics/traffic/Annual+US+Traffic.htm>

<sup>3</sup> Brancatelli, J., Portfolio.com: Business Travel, October 23, 2007

<sup>4</sup> Federal Aviation Administration, 2001 Airport Capacity Enhancement Plan, Department of Transportation, Federal Aviation Administration Office of System Capacity (ASC-1), Washington, DC, December 2001, [http://www.faa.gov/about/office\\_org/headquarters\\_offices/ato/publications/bench/media/01\\_ACE.PDF](http://www.faa.gov/about/office_org/headquarters_offices/ato/publications/bench/media/01_ACE.PDF)

present delays in the terminal areas. However, industry analysts point to the commercial airlines' increased use of smaller planes such as Regional Jets (RJ) as partly to blame for increased congestion in the skies and on runways.

Currently, at many of the major “feeder” hubs such as LaGuardia (LGA), Boston (BOS), Chicago (ORD), Atlanta (ATL), and St Louis (STL), 40% of the arrivals/departures carry only 20% of the passengers. These latter flights are normally less than 300 nautical miles.<sup>5</sup> At New York airports, 26% of the operations carry only 6% of the passengers.

In the United States, typically sixty percent (60%) of all departures carry eighty percent (80%) of the passengers more than 300 nautical miles. Forty percent (40%) of aircraft operations carry only twenty percent (20%) of the passengers.

Growth in passenger demand was low for 2008, dominated by the increased cost of fuel through September and a slowing international economy. Economists and ecologists views vary widely as to the near term outlook, but it is true that the reduced growth has not improved airport congestion and delay. In fact, delays in 2008 and 2007 have been worse than previous years. Airport traffic in developing nations and heavily congested hub airports in North America and other developed nations will likely continue to grow.

The Boeing 2008 Current Market Outlook (CMO) is very positive, projecting a 5% annual growth in global air travel over the next 20 years, despite the overall economic down turn in 2008. Boeing forecasts a demand for 29,400 airplanes over the next 20 years. A breakdown of that demand is for 980 units of 747 and larger aircraft, 6,750 units of twin-aisle aircraft, 19,160 units of single-aisle aircraft, and 2,510 units of regional jets. The civil transport rotorcraft could compete with regional jets over distances of less than 600 mm, a claim justified later in this study, for partial replacement of turboprop and small regional jets. That would free up runway slots for large capacity aircraft (single or twin-aisle), increasing airport throughput.

Based on the CMO, airport delays (and associated costs) can be expected to grow and capacity may languish, if the projected demand for more aircraft is realized.

### **2.1.3. Non-Solutions**

Very large aircraft are more efficient in terms of airline operating costs per seat-mile, just by the efficiency of scale. But very large aircraft naturally require a longer time to embark (every ticket must be checked and every carry-on must be stowed). It seems unreasonable to disembark over 400 passengers single file, so very large aircraft may need special gates for multiple simultaneous exit points. Even so, cleaning a very large aircraft to prepare for the next load will require longer as well. This author expects the added gate time at the terminal will prevent any improvement in gate utility or airport throughput for a fixed number of gates. Limited by runway size and load, the need for special gates and the limited application of very large aircraft to routes with high passenger demand for common departure and destinations, it is unlikely that very large aircraft are the panacea to reduce delays or increase throughput in the diversity of North America air traffic.

Conversely, smaller aircraft with nineteen to fifty seats are occupying runway occupancy times that could be used by larger aircraft with greater available seating capacity. The Regional Airline Association (RAA) reports that the average seating capacity of reporting members is 36 seats per member aircraft and

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<sup>5</sup> Federal Aviation Administration, 1997 Airport Capacity Enhancement Plan, Washington, DC, December 1997

46 seats per regional jet (RJ).<sup>6</sup> RJ's are generally smaller than the jets in the major commercial airline fleets, with current models' seat capacities of 112 to 250 seats (Boeing 737-700 seats 112 in the two-class configuration). Most current model turboprops have between 32 to 50 seats, but the trend is clearly upwards, settling out just below 100 passengers.

Yet each aircraft arrival and/or departure requires an arrival slot, a runway occupancy time. Replacing a 200 seat aircraft with one having only 32-85 seats creates an immediate passenger throughput problem, since that allotted runway occupancy time would then carry fewer passengers.

## 2.2. V/STOL Operational Concept

The FAA Eastern Region's Newark (EWR) Capacity Study suggests a proven way to alleviate airport runway congestion and increase airport throughput. It is based on reduction of demand for the primary instrument runway surfaces, first by funneling smaller aircraft and capable RJ's to non-primary runway surfaces and secondly by enabling judicious use of vertical flight-capable (V/STOL) and enhanced short takeoff and landing (ESTOL) aircraft to operate from separate very short STOL runways; or from VSTOL Takeoff and Lift-Off area Facilities (TLOF) as detailed in the FAA Advisory Circulars [AC 150/5390-2B Heliport Design](#) and [AC 150/5390-3 Vertiport Design](#). A term commonly used to describe this category of operation is Runway Independent Operations (RIO) to distinguish it from the long expensive runways required by main airliners. The aircraft used in the RIO operation are referred to as Runway Independent Aircraft (RIA).

Examples of the new rotorcraft types that could operate from these separate TLOF areas are the tilt rotor with its unique capability to takeoff and land vertically, and improved and cost-effective helicopters like the SMRC. Conventional helicopters can also operate from these facilities, but their cruise efficiency is generally cost effective only over short ranges and therefore with smaller passenger loads consistent with the market demand for short routes.

The system named Simultaneous and Non-Interfering (SNI) is a proven concept of airspace traffic flow management using simultaneous, converging instrument approaches (SCIA)<sup>7</sup>, to IMC minima of 700/2<sup>8</sup> LNAV/VNAV RNP routes, and separated final approach and takeoff areas (FATO) to separate TLOF areas. Graphics of the TLOF and FATO are shown in Figure 2, from FAA Advisory Circular AC 150/5390-3.

This combination of vertical lift aircraft with SNI operations offers a tremendous economic potential to alleviate existing and future delays and to provide for increased capacity. Implementation of vertical flight aircraft and vertical-oriented air traffic management concepts such as SCIA and SNI procedures can provide simultaneous and non-interfering V/STOL and/or ESTOL operational solutions, thereby offloading the demand for runway slots. This operating concept implemented with additional large commercial aircraft partially filling the opened runway slots, can significantly reduce primary runway surfaces occupancy requirements, reduce delay while increasing passenger throughput, and improve NAS flexibility and productivity with increased safety.

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<sup>6</sup> Regional Airline Association, Top Regional Aircraft of 2004, [http://www.raa.org/aircraft\\_equipment/2004\\_top\\_aircraft.cfm](http://www.raa.org/aircraft_equipment/2004_top_aircraft.cfm)

<sup>7</sup> Federal Aviation Administration, A National Airspace System Performance Analysis Capability (NASPAC) Evaluation of the Impacts of the Center-TRACON Automation System (CTAS) on Airport Capacity, p. 11, <http://www.tc.faa.gov/acb300/techreports/TN9614.pdf>

<sup>8</sup> Federal Aviation Administration, FACT Plan Update and Capacity, Southwest Region Partnership Conference 2005, P. 16

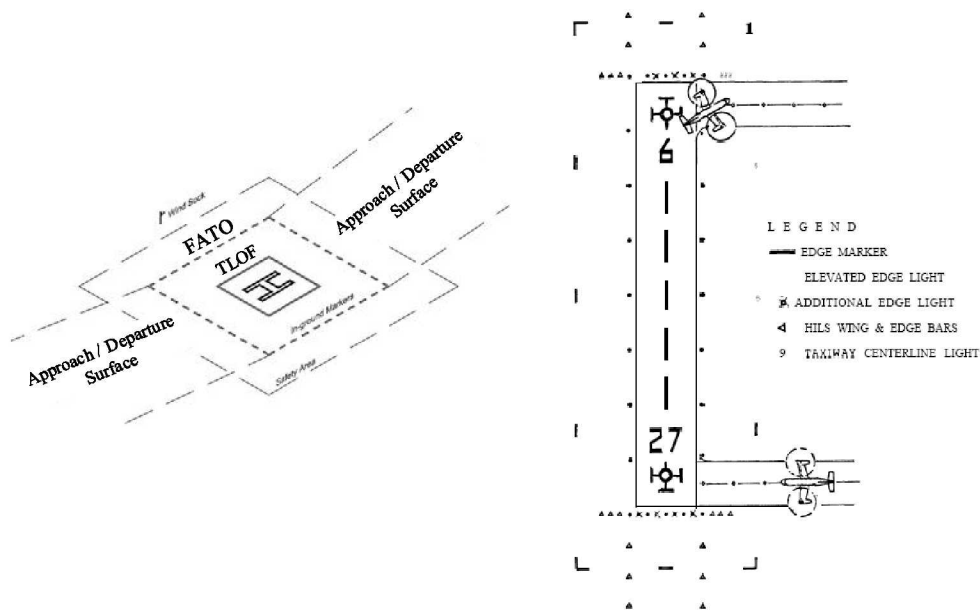


Figure 2. TLOF and FATO Areas for Helipad and Rollway Concept

With RIO and SNI, future rotorcraft can safely meet the increasing demand for passenger transportation in the US and around the world. The paradigm of air traffic management must be changed to accommodate SNI, or SNI-like concepts. Air traffic managers and passenger through-put and demand planners need to recognize these potential benefits and begin serious analysis. Infrastructure and facilities must also be designed and established at current congested airports that are selected to implement this new approach.

When the RJ or conventional jet is stuck on the ground by traffic delays, the SNI-capable ESTOL or V/STOL runway independent aircraft (RIA) can continue operations. Thousands of passengers have flown on Los Angeles Helicopters, New York Airways and San Francisco Helicopter Airways, not to mention Helijet International in Canada. And several European carriers use rotorcraft, such as British Helicopter Airways. There are V/STOL RIA operators in Europe today. These operations, coupled with SNI capabilities can make a tremendous difference in the movement of passengers. RIO operations can significantly reduce airport congestion and improve passenger throughput, where new runways or smaller capacity regional jets cannot.

The implementation of ESTOL and V/STOL technology coupled with the implementation of SNI is not without cost. But the FATO and TLOF areas, even elongated ones, are much smaller and therefore far less expensive than building 10,000 foot long new runways with associated long taxi-ways to accommodate more fixed wing demand. Further, additional runways still require additional gates. A fair comparison of costs is beyond this study, but would surely show this concept of V/STOL or ESTOL operations to provide the least expensive, most effective, and safest solution to increase airspace flexibility, predictability, and productivity through delay reduction and capacity increase in a future air traffic management system.

### 2.3. Necessary Vehicle Attributes

**External noise**, both measurable and virtual, is an issue that cannot be overlooked. It is an environmental problem in most communities and can cause the demise of the vertical flight industry's goal of integrating helicopters and tilt rotors into the transportation system. Implementation of steep (>9

degrees final approach segments) or “teardrop instrument penetration” approach paths can keep the majority of potentially objectionable noise within air facility boundaries.

**Public perception** of vertical flight aircraft is something that can, and must, be improved if helicopters and tilt rotors are going to fit into the air transportation system and be effective in efficiently moving people.<sup>9</sup> Certainly, any V/STOL aircraft in commercial operations will be certified to exacting standards. It must be safe throughout its operational envelope, in all modes of flight. But general public acceptance is also a necessary condition for successful introduction of a new type of aircraft. The joke that helicopters are 5000 parts flying in formation is not the desired public image.

**Internal noise, vibration and response to gust and air turbulence** are critically important to passenger comfort. Passenger comfort not only influences public perception, it is a matter of public acceptance. Passenger comfort and the experience of a pleasant journey must be considered, in contrast to the journey that represents the last miserable flight a passenger decides to take in a commercial V/STOL. Passengers complaining of nausea from internal noise, vibrations, and uncomfortable buffeting from air turbulence at the end of a two hour flight can quickly spread to be perceived as a “typical” V/STOL ride.

It is the authors’ opinion that public perceptions can be favorably swayed with well designed V/STOL aircraft and good passenger experiences. But public acceptance, once lost, may requires years of diligent effort to regain.

## **2.4. Necessary Facilities**

Facilities for V/STOL operations should minimize the environmental impact while maintaining the convenience of access to air travel. must be done to have an optimum air transportation system in place to help share the load of the increased demand for travel in the future.

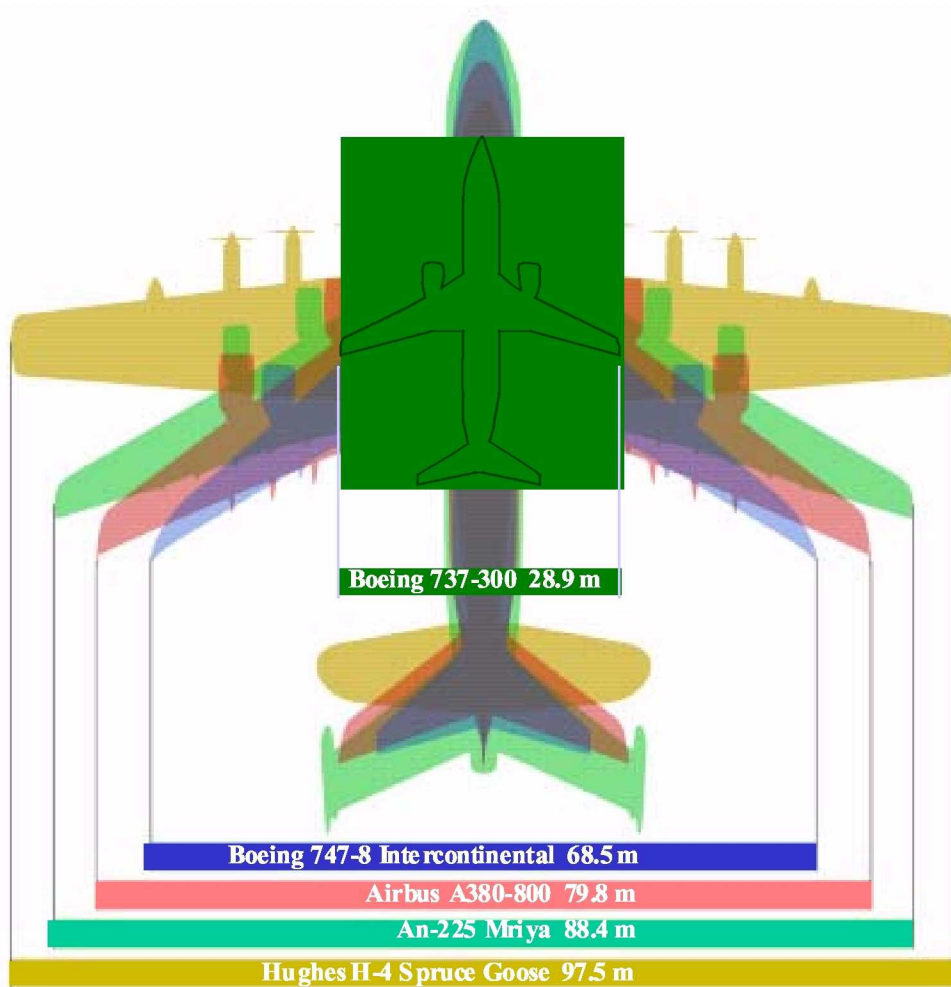
Facilities include dedicated FATO and TLOF surfaces and procedures that provide for many operations per hour, similar to runway utilization. The TLOF should have sufficient separation from the passenger terminal area to avoid exposure of ground support personnel and parked aircraft from the noise, downwash and debris that may be associated with normal takeoff and landings. Taxi ways must be provided connecting the passenger terminal to the TLOF. The taxi way must be adequate for both arriving and departing rotorcraft, and accommodate a few rotorcraft waiting in line for takeoff.

The passenger terminal area would, ideally, include completely enclosed walkways connecting the parked aircraft to the V/STOL passenger terminal. It is envisioned that future V/STOL aircraft would remain below 100 passengers for many years, as turboprop and RJ’s have done during their introductory periods. Thus, the aircraft are not large and do not require long walkways. Likewise, spacing between gates can be closer than the general purpose gates for fixed wing commercial aircraft that need to accommodate a wide range of aircraft sizes. For reference, the single aisle 737 has a 94’ 8” wingspan, the twin aisle 777 has a 200’ wingspan, and the advanced 747-8 has a 224.8’ wingspan. This is dramatically shown by the overlay in Figure 3. Early future V/STOL are certain to be smaller, sized for fewer passengers, allowing a more compact V/STOL terminal.

Implementation of facilities for ESTOL and V/STOL aircraft in combination with the proven capability of SNI procedures, can provide feeder regional commuter aircraft with simultaneous and non-interfering V/STOL runway independent operations. This capability significantly reduces the number of operations required on the primary runway surfaces thus reducing delay while increasing the airport’s (and the NAS) flexibility, productivity with increased safety.

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<sup>9</sup> Tilt rotor and Advanced Rotorcraft Technology in the National Airspace System (TARTNAS) Final Report, p. 53



**Figure 3. Overlay of Several Fixed Wing Commercial Aircraft**

## **2.5. Operational Enablers**

### **Problem**

External noise is an issue that can not be overlooked. It is an environmental problem in most communities and could cause the demise of the vertical flight industry's goal of integrating helicopters and tilt rotors into the transportation system.

### **Solution**

Implementation of steep final approach segments (>9 degrees) or "teardrop instrument penetration" approach paths can keep the majority of potentially objectionable noise within air facility boundaries.

V/STOL aircraft can turn shorter, climb steeper and descend steeper than conventional fixed wing airliners when designed to that criteria. Compared to a conventional regional-size turboprop aircraft (SAAB 340 or DHC-8-100) or a regional jet, the tilt rotor can turn shorter (3872 foot radius @ STD rate turn at 60 ktas versus 7741 feet @ 120 ktas), and climb or descend steeper at a slower airspeeds (50-70

kcas) at steeper angles (>55° climbing to 12-15 °descending).<sup>10</sup> Vertical flight rotorcraft or powered lift air vehicles can also execute steep descent profiles (like the turbojet) at maximum Mach speed using GPS-based RNAV/BRNAV navigation guidance, then rapidly decelerate to rotor-borne flight in helicopter mode and complete a steep IMC instrument approach (9-15 degrees) to either a hover or the ground. This has the potential to reduce final approach segments (enabling shorter, steeper GPS precision approaches) of 2.5 nm for a tilt rotor 12 degree approach versus 5.0 nm for a 3 degree conventional aircraft approach.

A powered lift air vehicle needs only a prepared surface to land and takeoff. A Final Approach and Takeoff area of 300 by 300 feet with a TLOF surface of roughly 150 feet by 150 feet is adequate for vertical operations. A “rollway” TLOF of approximately 600-800 feet may be required for STOL operations, with appropriate TERPS protected obstruction clearance planes.<sup>11</sup> This rollway size was predicated on a vehicle of approximately 65,000 lbs at 95° F at Sea Level. Such a vehicle could carry approximately 40-50 passengers with appropriate luggage and/or cargo.<sup>12</sup>

Enhanced short takeoff and landing aircraft, ESTOL, are not vertical lift, but do exhibit excellent short field performance and have demonstrated some of the steep approach concepts proposed here. The DeHavilland of Canada DASH-7 (DHC-7) can takeoff in approximately 2500 feet from a flat surface with no wind to 35 feet AGL on a standard day at a maximum takeoff gross weight of 44000 lb in STOL takeoff configuration with 25° flaps at sea level (SL). .. The V1, V2 and V35 are 76, 84 and 86 KIAS respectively.<sup>13</sup> For the same conditions the ESTOL DHC-7 required a maximum landing field length of 2200 feet with 45° flaps at 1.3V<sub>S</sub>.<sup>14</sup> DASH -7 land and hold short (LAHSO) operations on Runway 33 at Washington National (DCA) routinely used only 900 feet.

## **Problem**

Public perception of vertical flight aircraft can and must be improved to become an accepted part of the air transportation system and aid in passenger throughput.<sup>15</sup>

## **Solution**

Develop V/STOL infrastructure and facilities that minimize the environmental impact and offer passengers convenient access to air travel for an optimum air transportation system that will be able to handle the increased demand for future air travel.

The nature of this solution has been recognized and reported in several previous studies. The most comprehensive report was the CTRDAC<sup>16</sup> report, which identified among many things the disparity of who pays to develop the infrastructure and who benefits from that infrastructure. This is not a technical issue. But air traffic delays ricocheting through the whole network when one airport experiences major

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<sup>10</sup> NASA-Boeing Study, “Rotorcraft Requirements in the Next Generation Air Traffic Management System”, Section 3, p3-13

<sup>11</sup> Bell-Boeing/NASA Ames, “Civil Tilt rotor Missions and Applications Phase II: A Research Study – Final Report”, for FAA/NASA/DoD, NASA CR 177452, Boeing, Seattle, WA, July, 1987

<sup>12</sup> Bell-Boeing/NASA Ames, “Civil Tilt rotor Missions and Applications Phase II: A Research Study – Final Report”, for FAA/NASA/DoD, NASA CR 177452, Boeing, Seattle, WA, July, 1987

<sup>13</sup> DeHavilland Canada, DASH 7 Flight Manual, Section 4, pp. 4-5-17/18, Figures 4-5-9 and 4-5-10

<sup>14</sup> DeHavilland Canada, DASH 7 Flight Manual, Section 4, pp. 4-8-19, Figure 4-8-9

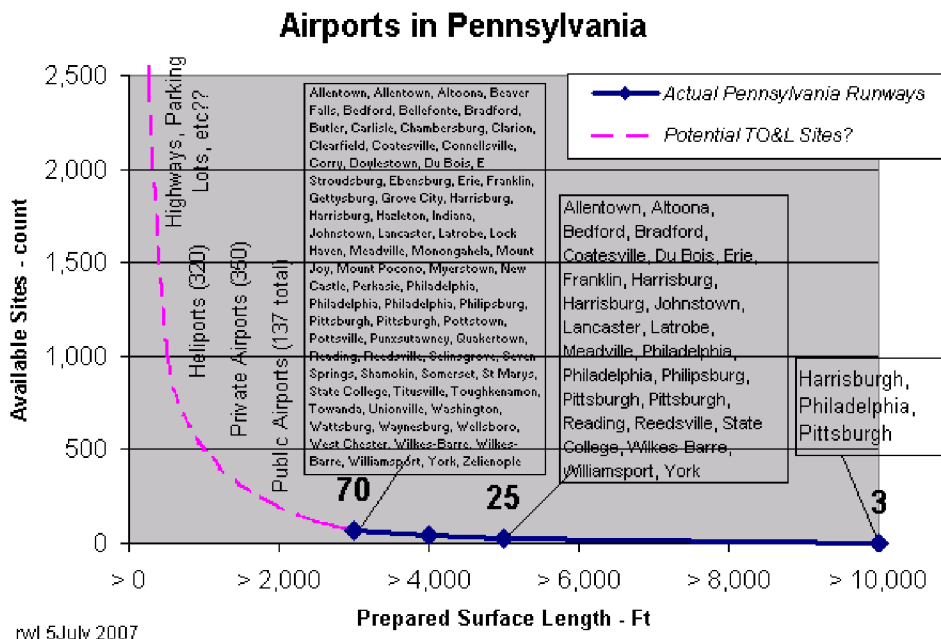
<sup>15</sup> Tilt rotor and Advanced Rotorcraft Technology in the National Airspace System (TARTNAS) Final Report, p. 53

<sup>16</sup> Civil Tiltrotor Development Advisory Committee (CTRDAC), Report to Congress, Vol I & II, ref PL102-581, December, 1995

delays is clearly a national issue, and it has more public awareness today than ever before. That makes it a policy issue, and that is probably a necessary prerequisite for action.

While “feeder” routes are not a justification for rotorcraft to relieve airport congestions, they readily offer a secondary function if significant numbers of rotorcraft were in service.

Figure 4 shows there are three major airports in Pennsylvania with 10,000 ft runways (Harrisburg, Pittsburgh and Philadelphia). But there are over 90 Pennsylvania sites with prepared surface runways from 3000 to 5000 feet, which are more than ample to support rotorcraft operations.



**Figure 4. Potential Landing Sites In Pennsylvania**

## Problem

Rotorcraft downwash and outwash are perceived problems.

## Solution

The TLOF should be located away from areas where passengers embark and deplane, to minimize interference with taxiing aircraft. No personnel are in the vicinity of the TLOF, just as no personnel are standing around on runways.

Ground service vehicles and associated ground service personnel will not be endangered by V/STOL downwash since the aircraft will ground taxi from the TLOF to an appointed parking spot, and shutdown. Passengers will deplane under protective awning-covered walkways on surface parking aprons, to reach the main terminal, similar to existing operations at most facilities today. Taxi to and from the TLOF requires far less thrust from the rotors than takeoff and landing and will generate low ground wash velocity.

Thus the outwash from a taxiing rotor does not pose a danger to nearby ground crew, who should already be at a safe distance before taxi begins, much like standard operations for fixed wing aircraft. If the TLOF is a roof-top facility, similar facilities may be employed or escalators/stairs may be used to conduct the passengers down into the terminal complex where they will have access to normal moving walkways, etc. For roof-top facilities, the gates will be below the TLOF/parking areas, with access again



via weather-protected escalators or stairs. Storable weather coverings can be used to provide protection for passengers from the gate access stairs to the aircraft doors.

### Problem

Vertical lift aircraft are slow and do not meet the normal fixed wing approach requirements.

### Solution

Rotorcraft and powered lift aircraft do not need to operate from conventional runways, but should operate safely from smaller final approach and take-off areas (FATO) separated from airport runways. The practical reasons for that operation, as previously described, actually enhance throughput of the airline passengers.

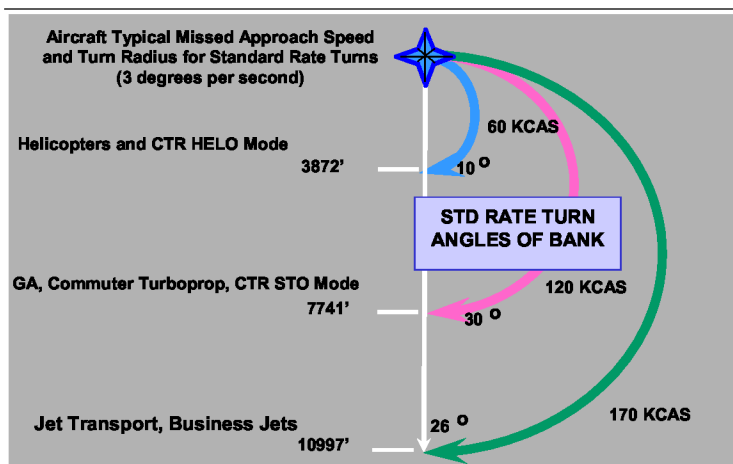
Vertical flight IFR operations require the same handling priorities and considerations as fixed-wing aircraft. The unique flight characteristics of vertical flight aircraft enable some unique but complementary air traffic handling procedures and TERPS criteria, that enable safer and more efficient operation in constrained airspace of the National Airspace System. In order to fully exercise the unique capabilities of rotorcraft, precision and non-precision TERPS must be developed around their unique performance characteristics.

Rotorcraft flight performance envelopes are quite distinct from that of the conventional aircraft, in that they have a very slow to zero speed capability at the low end of their performance curves. These capabilities must be used in procedural development and regulations to enable air traffic managers to make best use of the aircraft in traffic management.

Vertical flight aircraft offer the opportunity to safely execute approaches at steep angles. Helicopters can approach at angles up to six or even to nine degrees while tilt rotors may be capable of safe approaches up to 15-deg. Steep approach angles offer several advantages over conventional approaches.

Vertical flight aircraft can turn comfortably and with complete control at nominal approach speeds of 60 to 70 knots. Turns at these low airspeeds result in dramatically reduced turning radii, as the examples shown in Figure 5.

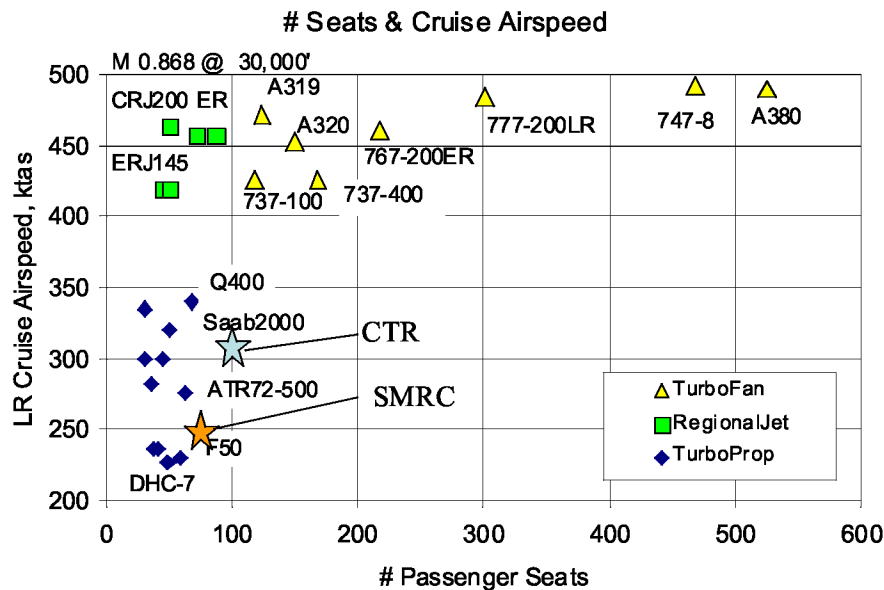
**Figure 5. Turning Radii of Rotorcraft versus Conventional Fixed Wing At Slow-speed**



### 3. Civil Transport Mission Profiles

Mission definitions for the CTR and SMRC were derived by examining the block speed and delay times for existing turboprops and regional jets (RJ). Passenger seating capacity was selected on the basis of current aircraft trends, adopting the well established market driven trend.

A general trend was found between number of passenger seats and aircraft cruise airspeed, shown in Figure 6. All turboprop aircraft cruise at less than 350 ktas and have fewer than 80 passenger seats. The turbofan Regional Jets have cruise airspeeds near those of full size airliners, but were still sized for fewer than 90 seats. The more recent CRJ700 and CRJ900 have 70 and 86 seats, respectively, although there are new RJ developments with over 100 seats are anticipated. Accordingly, this study assumed a maximum of 100 seats for the civil transport rotorcraft.



**Figure 6. Trend of Passenger Seats with Aircraft Cruise Airspeed**

Figure 7 shows a sample of regional jets and turboprops that this class of civil rotorcraft may compete with. They are sleek, modern, very competitive aircraft. The SAAB 2000 entered service in 1994. It had good heritage, based on experience with its predecessor, the SAAB 340. It was longer, could carry up to 50 passengers and had a max cruising speed of 368 ktas at 25,000 ft altitude. It had efficient six-bladed slow turning propellers. This experience and technology gave the SAAB 2000 the highest cruise airspeeds of the commercial turboprops, but production was stopped in 1999 because the airlines saw marketing advantages to the new low-cost regional jets, the Bombardier CRJ and Embraer ERJ family.

Civil transport rotorcraft would not be competitive in the prevailing tight market with high fuel cost, and will not be tomorrow without a major infusion of new technologies. The total development cost of enabling technologies will be expensive, perhaps even prohibitive for some technologies. Those making the investment cut must offer a high return on investment (ROI) to make a new civil rotorcraft successful in this limited, competitive market.



**Figure 7. Examples of Turboprops and Regional Jets**

Fortunately, there are many technologies available that can contribute to a viable rotorcraft. These are identified and examined in this study, and evaluated for their ability to make an economically competitive commercial rotorcraft. The result, when all the advanced technologies are applied, is an astounding 41% reduction in rotorcraft empty weight, achieving operating costs that really are competitive with the best turboprops.

The Civil Tilt Rotor (CTR) with its potential 350-400 ktas cruise speed can be competitive with the high end of the turboprop range. A 100 passenger capacity was selected, staying within the defined bounds for the turboprop aircraft, shown in Figure 6.

The design airspeed selected for the SMRC concept is 250 ktas, considerably faster than current helicopters, and competitive with early turboprop aircraft. That airspeed was considered a good goal for this slowed-rotor concept, to stay within reasonable bounds of blade tip Mach number. The SMRC was sized for 75 passengers, on the high side of the turboprops designed for that airspeed, also shown in Figure 6.

Table 1 shows FAA requirements for the number of flight attendants versus the number of passenger seats. Both the 100 passenger CTR and the 75 passenger SMRC aircraft required two attendants.

**Table 1. Number of Required Flight Attendants (FAA 125.269)**

Number of Passengers	Number of Flight Attendants
> 19 and < 51	1
> 50 and <= 100	2
> 100 and <= 151	3

### 3.1. Selecting Viable Mission Ranges

CTR and SMRC mission ranges were selected to be competitive. That determination was based on the block speed of the civil rotorcraft against that of current turboprop and Regional Jets. The gate-to-gate time includes delays on the runway and in-flight, but does not include time at the gate for loading and unloading. This approach is an extension of that applied in a previous NASA study<sup>17, 18</sup>.

The Official Airline Guide (OAG) provides scheduled departure and arrival times for commercial airliners, RJ's and turboprops. This data was used to estimate the ground delay time built into these official schedules by comparing the ideal block time to the scheduled block time.

Data was collected for turbofan aircraft departing from LAX, CVG, EWR and BOS. These flights had scheduled flight times ranging from 45 minutes up to 15 hours. The equipment included B767, B757, B747, B737, A320, and MD80. A variety of RJ data was obtained for operations into Cincinnati from CHM, EWR, ORD, BGR, MSP, and DAY. These flights ranged from 43 minutes up to 2 hours 48 minutes. A smaller group of RJ data was collected for BOS to DCA, PHX to LAX, and PHL into LGA.

Block speed (ktas) was calculated as the point to point distance (nm) divided by the block time (scheduled gate-to-gate time, hours), where schedule times were taken from the OAG, and the distance was that between city pairs.

Figure 8 shows block speed versus range, and fairly distinctive trend lines for turboprop and RJ operations. RJ departures from Newark and LaGuardia showed a slightly different trend than the other RJ data. A few data points also identified that the departure time-of-day effects block speed, presumably by increasing ground time due to heavy air traffic.

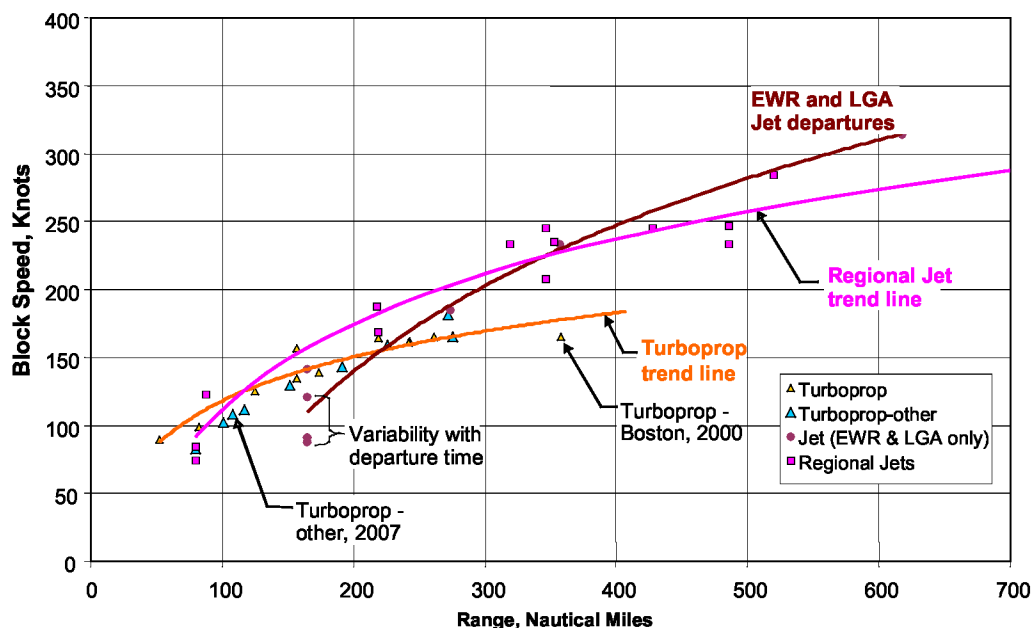


Figure 8. Block Speed Versus Mission Range

<sup>17</sup> Advanced Vertical Lift Configuration Study, Task Order #1, NAS2-01064, 2001

<sup>18</sup> Williams, R, Rosenstein, H, Wilkerson, J. "Advanced Vertical-Lift Configuration Studies"; Presented at the American Helicopter Society Powered Lift Forum 58, June 12, 2002, Montreal, Canada

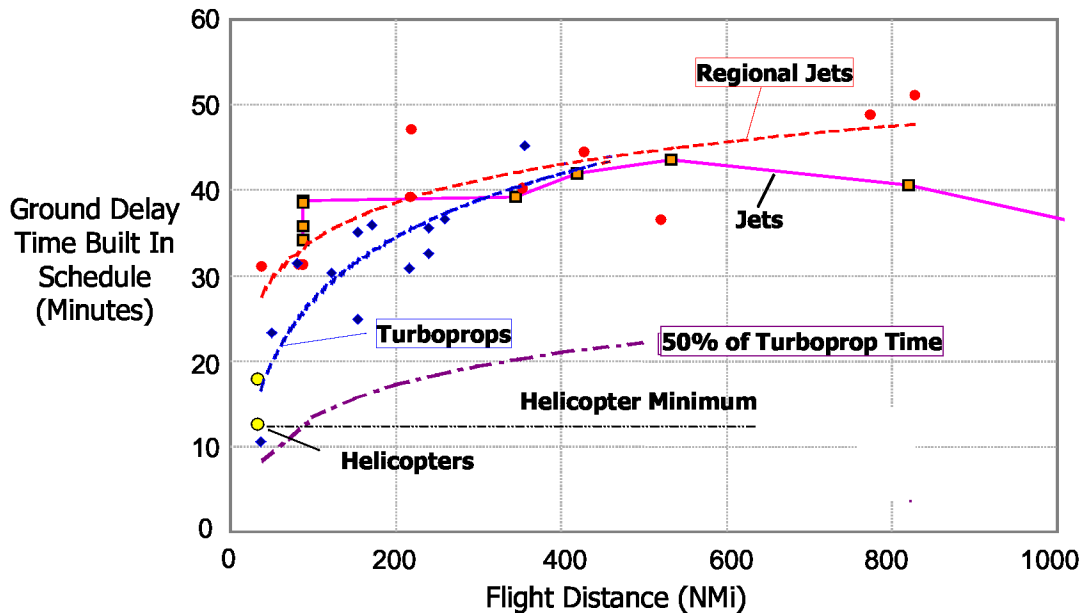
Scheduled block time ( $t_b$ ) can be expressed as shown below, where the “ideal block” time is defined as the distance between city pairs divided by the aircraft’s cruise speed:

$$t_b = t_{\text{gnd taxi+delay}} + t_{\text{ideal block}} + \Delta t_{\text{climb}} + \Delta t_{\text{takeoff\&landing}}$$

$$\text{where: } t_{\text{ideal block}} = \left( \frac{\text{Distance}}{V_{\text{cruise}}} \right)$$

Ground taxi and delay time was estimated with the above equation, using known values for the distance to the destination, the cruise airspeed of the aircraft ( $V_{\text{cruise}}$ ), and the OAG block time ( $t_b$ ). A 6% allowance was added for the additional time for takeoff, landing and climb. The resulting estimated ground time demonstrated a clear increase with the distance flown, although not a linear increase, and overlapping bands for large turboprops, regional jets, and turboprops.

Figure 9 shows ground time and delay time trend lines for RJ and turboprops increase to asymptotic limits with the distance flown. The helicopter data points demonstrate that quick turnaround and tight schedules are feasible, for small numbers of passengers. This study adopted a ground delay time of 50% of the turboprop trend as a basis of comparison for civil rotorcraft competitive analysis. Note that part of this assumed reduction in delay time is expected to be gained from vertical flight operations where the TLOF is physically closer to the terminal, thereby reducing ground taxi time.



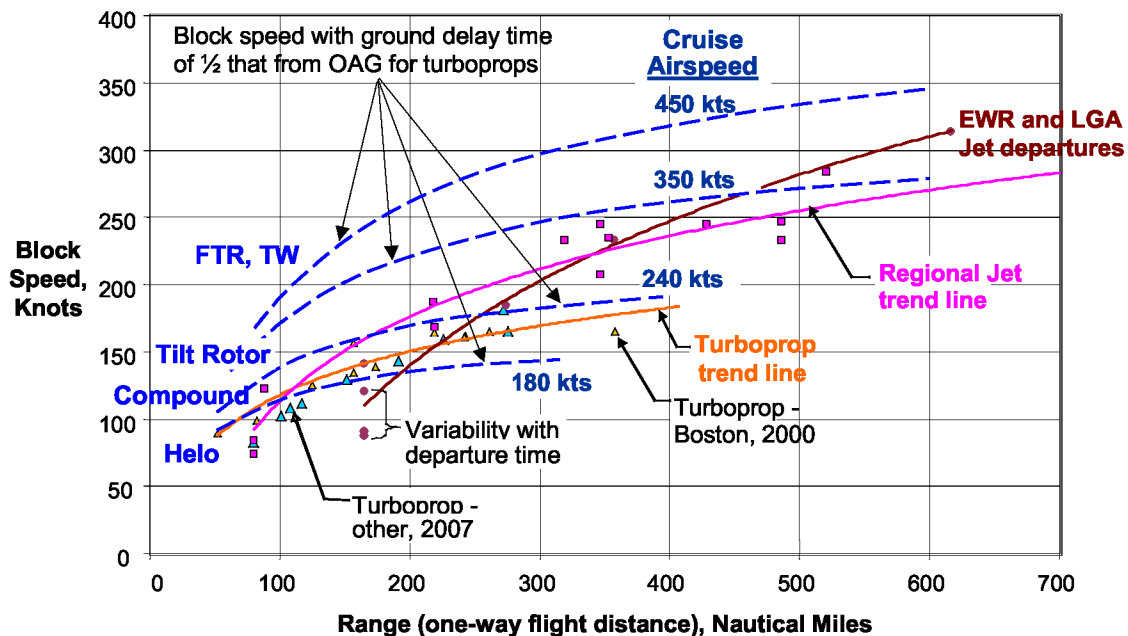
**Figure 9. Trends of Ground Time Versus Flight Distance**

Block speeds of potential civil rotorcraft were then estimated for comparison to the data in Figure 8. Four rotorcraft concepts were picked with an appropriate cruise airspeed for each. The ideal block time was calculated for each as a function of range. The ground delay time was added to this (50% of the RJ delay time), and the same additional 6% time allowance to account for take-off, climb and landing over and above the ideal block time. The approximate rotorcraft block speed was then the distance flown divided by the sum of the rotorcraft ground delay time + ideal block time + the 6% allowance for take-off, climb and landing.

The four rotorcraft concepts were:

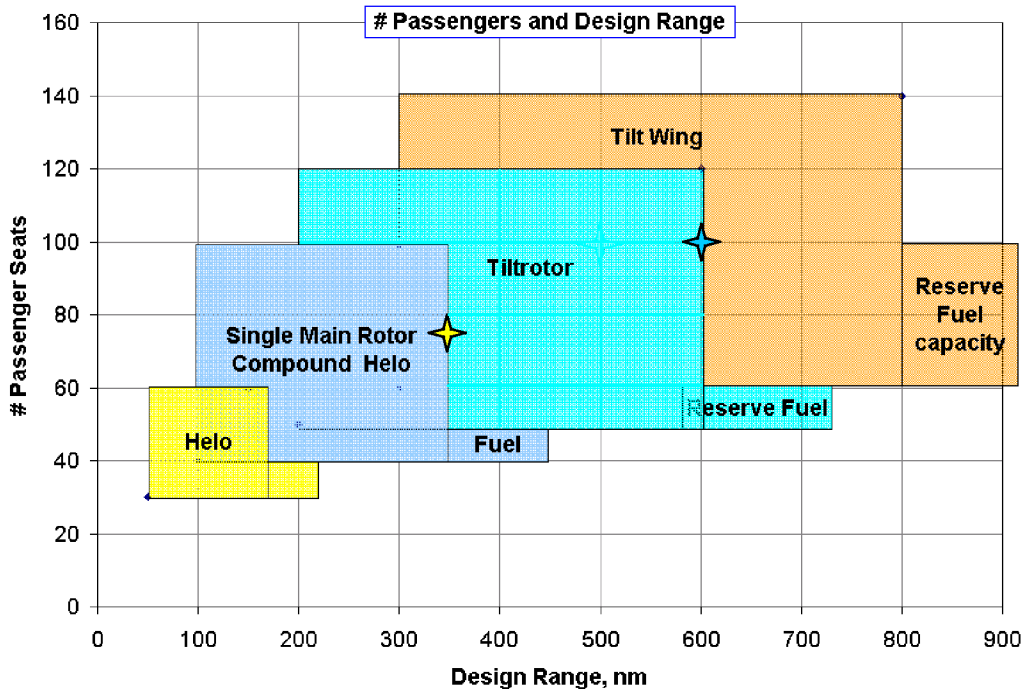
- Tiltwing (TW) with an estimated speed potential of 450 ktas
- Tilt rotor (TR) with an estimated speed potential of 350 ktas
- Compound helicopter with an estimated speed potential of 240 ktas
- Conventional helicopter with an estimated cruise speed of 180 ktas

Figure 10 shows how these four rotorcraft block speeds compare with existing turboprops, RJ's and commercial turbofan aircraft. The Tiltwing cruising at 450 ktas far exceeds the conventional jets on block speed, making it competitive up to 700 nm range or beyond. This is not surprising, given that our assumption was for smaller aircraft (around 100 passengers) with less ground delay time. The tilt rotor cruising at 350 ktas performed well, maintaining higher block speeds than jets and RJ's up to 500 or 600 nm range. The Compound helicopter cruising at 240 ktas had block speeds competitive with jets and RJ's up to 250 nm. And it's block speed remained better than the trend of turboprop block speed at ranges up to 400 nm. Finally, the helicopter with its 180 kit cruise speed was marginally competitive up to about 130 nm.



**Figure 10. Estimated Competitive Ranges for Four Civil Rotorcraft**

The selected regions of mission range and number of passengers for the four original civil transport rotorcraft concepts are graphically shown in Figure 11.



**Figure 11. Rational Number of Passengers and Range for Several Civil Rotorcraft**

The Civil Tilt Rotor (CTR) and the Single Main Rotor Compound (SMRC) helicopter were analyzed further in this study. The specific combination of passenger seats and design range selected for each were previously indicated by the colored stars:

- Civil Tilt Rotor: 100 passengers and 600 nm range
- Single Main Rotor Compound: 75 passengers and 350 nm range.

### 3.2. Mission Profile

The overall mission profile modeled the necessary FAA regulations for Transport Category aircraft flying under instrument flight rules (IFR), summarized in Table 2.

Specifics of the mission profile, described in Table 3, are sufficiently representative for conceptual design of these civil transport rotorcraft and evaluation of the benefits of advanced technologies, which is the end-goal of the study. The design takeoff condition for the rotor was at 2,000 / ISA+20°C, which determined rotor solidity. The engines and transmissions were sized by either the power required for Category A OEI at this altitude, or power required for the target cruise speed and altitude. A 50 nm cruise segment was included for the required IFR alternate destination, flown at 99% best range at the cruise altitude. A separate mission segment accounted for the fuel required to re-convert and the landing approach. The reserve fuel segment was 30 minutes, flown at 5000 ft / ISA+20°C. A diagram of this simple mission profile is shown in Figure 12



**Table 2. FAA Instrument Flight Rules**

**§ 91.167 Fuel requirements for flight in IFR conditions.**

(a) No person may operate a civil aircraft in IFR conditions unless it carries enough fuel (considering weather reports and forecasts and weather conditions) to—

- (1) Complete the flight to the first airport of intended landing;
- (2) Except as provided in paragraph (b) of this section, fly from that airport to the alternate airport; and
- (3) Fly after that for 45 minutes at normal cruising speed or, for helicopters, fly after that for 30 minutes at normal cruising speed.

(b) Paragraph (a)(2) of this section does not apply if:

(1) Part 97 of this chapter prescribes a standard instrument approach procedure to, or a special instrument approach procedure has been issued by the Administrator to the operator for, the first airport of intended landing; and

(2) Appropriate weather reports or weather forecasts, or a combination of them, indicate the following:

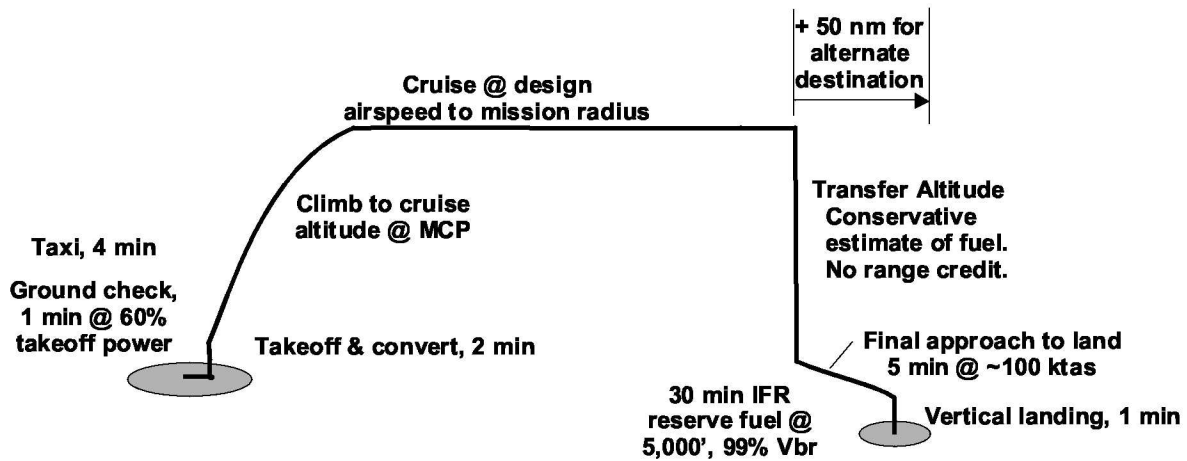
(i) For aircraft other than helicopters. For at least 1 hour before and for 1 hour after the estimated time of arrival, the ceiling will be at least 2,000 feet above the airport elevation and the visibility will be at least 3 statute miles.

(ii) For helicopters. At the estimated time of arrival and for 1 hour after the estimated time of arrival, the ceiling will be at least 1,000 feet above the airport elevation, or at least 400 feet above the lowest applicable approach minima, whichever is higher, and the visibility will be at least 2 statute miles.

**Table 3. Civil Rotorcraft Mission Profiles**

<b>Mission Segment</b>	<b>Altitude (ft), Temp (°F)</b>	<b>Time</b>	<b>Distance (nm)</b>	<b>Cruise Airspeed (ktas)</b>
Taxi, Warm-up	2,000, 88°F	4 min	NA	NA
Vertical Takeoff (HOGE)	2,000, 88°F	1 min	NA	NA
Climb	Altitude for best cruise		Part of cruise	max R/C @ NRP
Cruise @ 99% Best Range Speed, ISA	CTR 24,000 SMRC 20,000		CTR 600 nm SMRC 350 nm	CTR 305 ktas SMRC 250 ktas
Alternate Destination @ 99% Best Range	CTR 24,000 SMRC 20,000		50 nm	CTR 305 ktas SMRC 224 ktas
Transfer Altitude	SL	NA	NA	NA
Re-convert & Landing Approach	SL, ISA	5 min	NA	CTR 160 ktas SMRC 100 ktas
Vertical Landing	SL, 95°F	1 min	NA	NA
Transfer Altitude	5,000	NA	NA	NA
Reserve Fuel (IFR)	5,000, 77°F	30 min		CTR 220 ktas SMRC 195 ktas





**Figure 12. Civil Rotorcraft Mission Profile**

The selection of cruise altitude is significant. The concept for viable civil rotorcraft was not for conventional low-speed helicopters flying fewer than 10 to 30 passengers over short-haul routes at low altitudes. On the contrary, it was to carry 75 to 100 passengers over distances of 350 to 600 nm in the comfort of pressurized cabins at altitudes that are less affected by weather and turbulence. Cruise altitudes were selected for the best aircraft performance, as described later in this report in the individual sections for the CTR and SMRC designs.

## 4. Integrated Analysis

Boeing has developed several integrated multidisciplinary analysis (MDA) tool suites over the past four years, each addressing the unique characteristics of the rotorcraft concept it analyzes. They are collectively referred to as the Rotorcraft Conceptual Design and Analysis (RCDA) tool suites. The first was developed to support the Advanced Tandem Rotor Helicopter (ATRH) configuration for the joint services Joint Heavy Lift program conducted in 2006-07. This *RCDA-Tandem* tool suite was conceived to explore and optimize over a broad design space of vehicle and mission parameters in a fraction of the time that would be required for manual execution<sup>19</sup>. Since then, it has been applied in several other conceptual design studies.

Similar tool suites were developed in 2007 to support this study of the potential benefits of civil rotorcraft in the National Airspace, to reduce airport congestion and to improve throughput. These two versions are the *RCDA-TR* for a tilt rotor and *RCDA-SR* for a single rotor helicopter that can also be a compound helicopter.

All three tool suites were integrated using the ModelCenter software by Phoenix Integration, and they execute in that environment<sup>20</sup>.

### 4.1. ModelCenter

ModelCenter supports executable code like the Boeing legacy HESCOMP and VASCOMP sizing codes (FORTRAN), Excel files, text input and output files, and scripts. It also supports numerous other standard software products such as MathCAD and the PRICE cost estimating model, which is used in the RCDA tool suites. ModelCenter offers several features that greatly enhance its utility for design problems.

- Wrappers identify each module and all the applicable input and output data by name. The user decides on the naming convention and grouping of data, which can, conveniently, be different in ModelCenter from names and groups in the source code.
- The Link Editor shows all input and output data for each module in the tool suite. Output data from one program is linked to the input of another program with a drag and drop process. Likewise, groups of like-named data and arrays of data can be linked by dragging an output group to another module's input group.
- The Converger provides an easy means to implement an iterative solution. The user identifies the source of starting values and re-calculated values, by module and data element within the module. Settings allow the user to specify convergence criteria and to place limits on the allowable number of iterations.
- The Parametric Tool allows multiple values of a single variable to be run through the tool suite. All data can be recorded or only specified output data. An X-Y scatter plot is generated for each specified output parameter.

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<sup>19</sup> Joel Hirsh, Joseph Wilkerson, and Robert Narducci, "An Integrated Approach to Rotorcraft Conceptual Design", Paper AIAA-2007-1252, presented at the AIAA 3<sup>rd</sup> Annual Symposium, Reno, NV, Jan 11, 2007

<sup>20</sup> ModelCenter® Basics, © 2007 Phoenix Integration, Inc., Blacksburg, VA

- The Carpet Plot Tool allows the user to vary two independent variables, specifying the range of each. It generates a carpet plot, or a contour plot, or a surface plot for each selected output parameter.
- Several optimizers are available for ModelCenter. The included Optimization Tool implements a minimization algorithm based on a sequential quadratic programming method for solving nonlinear optimization problems.
- The Design Explorer (DE) optimization package was developed by Boeing and is licensed to Phoenix Integration. It is available as an add-on. DE is a more powerful optimization package allowing multiple independent variables, and it has a variety of built-in methods to explore the chosen design space, such as Full Factorial and Latin hypercube. Two distinct advantages of Design Explorer are its ability to (1) function well even in the presence of "noisy" objective and constraint functions and (2) efficiently do a global search of the design space. It is less likely than many other algorithms to get trapped in a local minimum/maximum.

The ModelCenter environment lists every module and its input and output data on the left hand side of the display, and provides a graphical display of the modules with data links on the right hand side, shown below in Figure 13.

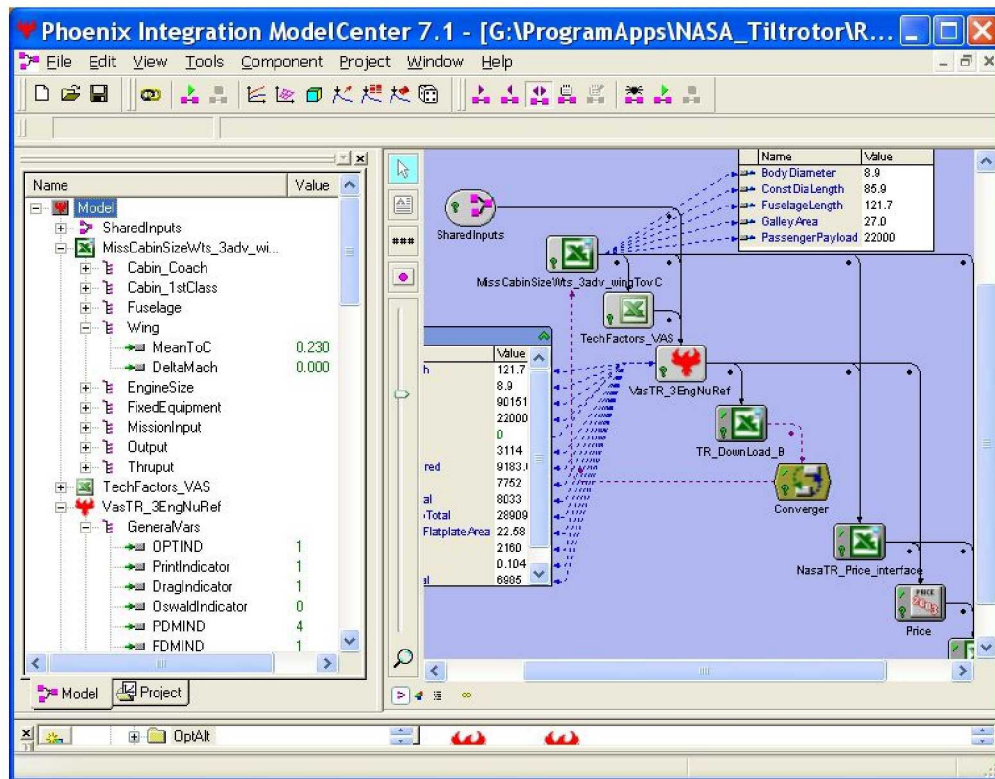
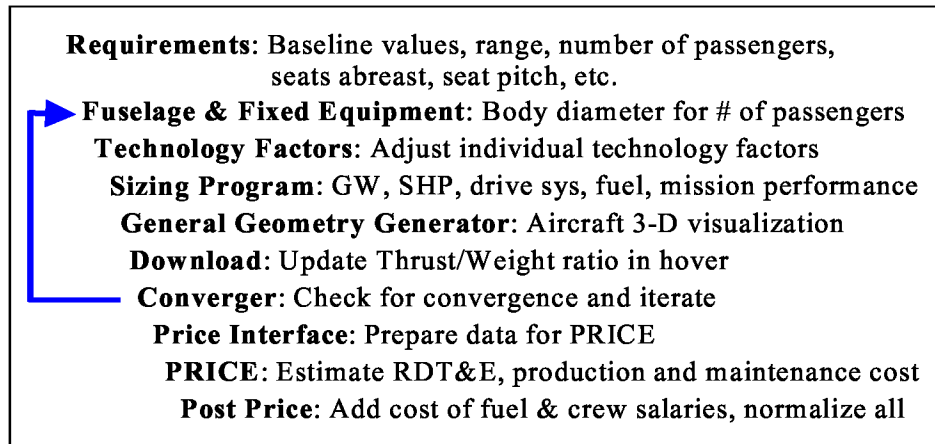


Figure 13. Typical ModelCenter Environment

## 4.2. Aircraft Conceptual Design Models

Integrating modules from other disciplines with the legacy sizing code enhances the fidelity and utility of the conceptual sizing, providing immediate assessment of air vehicle characteristics that are not part of the legacy sizing code. A consequence of an integrated MDA analysis has led to a better understanding of

the interaction between technical disciplines. The *RCDA* model is shown schematically in Figure 14, and a short explanation of each module is provided in Appendix A.



**Figure 14. RCDA Modules And Sequence**

Sizing and performance analysis of the Civil Tilt Rotor is performed by *RCDA-TR*, using the legacy VASCOMP program. Sizing and performance analysis of the SMRC is performed by *RCDA-SR* using the legacy HESCOMP program, with its built-in options for compound helicopters.

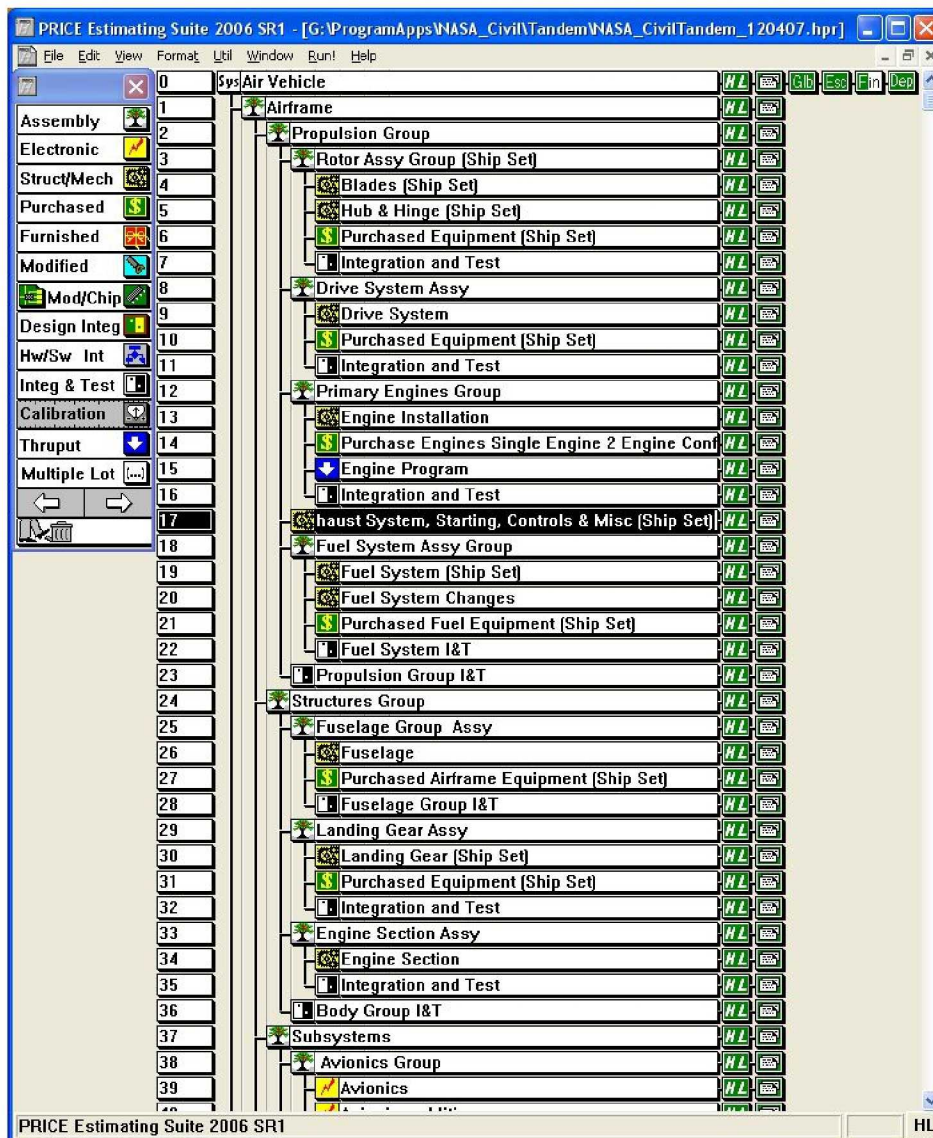
### 4.3. PRICE Models for Civil Rotorcraft

The PRICE model was calibrated by applying company program experience with development and production costs of similar products. Rotorcraft program history (V-22, CH-47, and Apache) was used in the calibration of the PRICE models used in this study. These parametric cost estimates are calculated by the PRICE cost module;

- RDT&E costs include all engineering development activity, tooling, bench tests, ground tests, prototypes & flight tests
- Production costs include all manufactured parts, purchased equipment and touch labor to build and assemble a complete aircraft
- Operating and Support (O&S) costs include unit level consumption (POL, consumables and repairables), depot maintenance, and sustaining support

The PRICE models for this study were set up in a standard Work Breakdown Structure (WBS). The portion of a WBS in Figure 15 shows components of the Structures Group, Propulsion Group and beginning of the Subsystems.

Elements were calibrated to relevant data from existing products and then modified by applying Boeing Lean manufacturing, advanced composites, and cost savings learned from Boeing Commercial Aircraft. Boeing has incorporated a philosophy of a common design tool set (CATIA V5 All Teams, Partners and Suppliers). This results in significant reductions in rework, engineering design changes, and engineering support. Significant reductions in assembly jigs and tools (determinant assembly) have also been achieved. A market driven target cost philosophy coupled with life cycle product teams was employed in the model resulting in a significant reduction in recurring costs and life cycle costs. These proprietary adjustments are not explicitly identified in this report, but are embedded in the cost model and are reflected in the cost estimates.



**Figure 15. Sample PRICE Model**

Many elements of an aircraft are purchased from vendors, referred to as “Buy” elements by cost estimating. Engine cost is a good example of a Buy element. These are fixed numbers when estimating the cost of a known product. All the Buy elements were converted to Build elements for this study, so their cost would float appropriate to the size and weight variations of the conceptual design.

O&S costs are initially set up and based on Boeing historical field data. The field data is used to establish an O&S baseline for the PRICE model. This O&S baseline is then adjusted and optimized based on new engineering design processes, lean manufacturing, and commercial applications. The PRICE Life Cycle model is calibrated using a combination of system level historical Mean Time Between Failures (MTBF) and predicted MTBF based on new engineering design processes, technologies, and the application of commercial practices.

## 5. Assessment of Costs

### 5.1. Cost Estimating Ground Rules

Ground rules for cost estimating were established early in the study in concurrence with the parametric cost estimating team to ensure the desired consistency with previous studies and to provide guidance to the cost estimating team. The high-level ground rules are shown in Table 4.

**Table 4. Cost Ground Rules**

Item	Cost Basis
Year Dollars	2007
Utilization	2500 Flight Hours/Year. = (8 FH / day) * (7 day/week) * (45 wk/yr)
Number of Flight Crew	2
Number of Cabin Crew	2 Cabin crew for SMRC and for CTR
Overall Operating Cost / FH	Acquisition + Support + Fuel, Salaries, etc
Initial Spares	2 year supply
Main Rotor Hub & Gearbox TBO	3500 FH
Aircraft Produced / Yr	30
Number Aircraft Produced	300

There are direct costs and indirect operating costs, as defined and used in Conklin & deDecker's "The Aircraft Cost Evaluator"<sup>19</sup>. This document is published for helicopters, turboprops, and jets in corporate service and can be purchased directly from Conklin & deDecker. Direct Operating Costs (DOC) are generally those that are incurred from aircraft usage. They are:

- Fuel (\$5.00 / gal)
- Oil & Lubrication (3% of fuel cost)
- Airframe Maintenance (PRICE Life Cycle Cost Model)
- Landing Fees (average \$26 / FH for corporate aircraft)
- Crew Expenses (incidental, such as overnight stays)
- Supplies & Catering (food, beverages, water, cleaning services)

The indirect operating costs are incurred by the airline operator independent of the aircraft usage, including:

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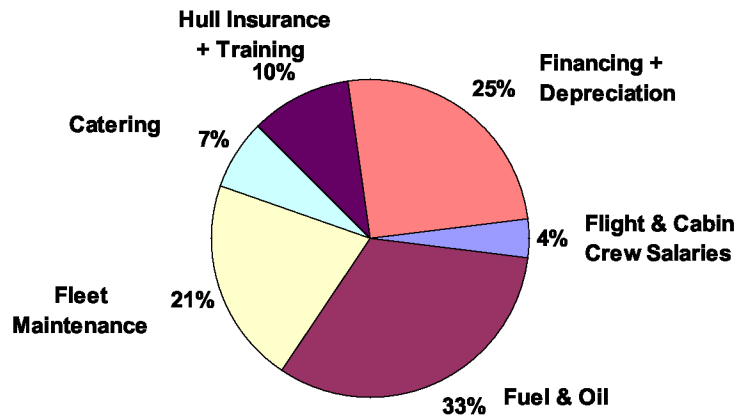
<sup>19</sup> Conklin & deDecker, "The Aircraft Cost Evaluator", 2007



- Flight Crew Salaries and Benefits
- Cabin Crew Salaries and Benefits
- Hanger Costs
- Hull Insurance
- Depreciation
- Financing
- Training
- Navigation and Weather service
- Refurbishment

A breakdown of the estimated total operating cost for a fleet of 50 CTR aircraft is shown in Figure 16 as percentages of the total \$/FH. Maintenance, fuel and oil consumed 54% of the total operating cost.

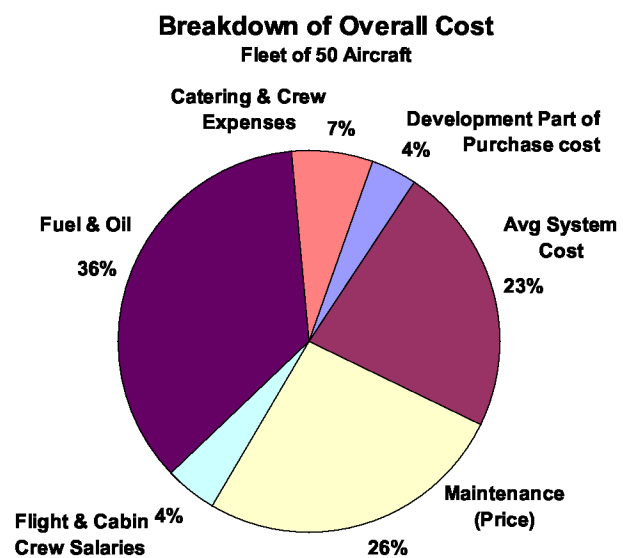
**Figure 16. Typical Breakdown of Operating Cost**



Life Cycle Cost (LCC) is often referred to. It includes the acquisition cost (reflecting a spread of the development cost), operating costs of the aircraft (including fuel and oil and all maintenance costs, but excluding costs not directly related to the aircraft, such as crew salaries and catering), and disposal costs (especially in the future “green” environment that may dictate careful disassembly for recycling).

A breakdown of the estimated overall costs for the CTR is shown in the pie chart of Figure 17 for a notional fleet of 50 aircraft out of a production run of 300 aircraft. Adding 50/300 of the aircraft development cost to the average system cost provides a rough estimate of the acquisition cost, excluding the cost of money (financing). That acquisition cost is 27% of the overall costs for a 30 year period of operations. Fuel, oil and maintenance make up 62% of the overall cost.

**Figure 17. Typical Breakdown of Overall Cost**



## 5.2. Cost Metric

There are many possible cost metrics. Some refer to productivity of delivering cargo, such as ton-miles/hour or \$/(ton-mile). Others have been used to compare the productivity or relative efficiency of competing aircraft, like (ton-miles/hr)/(Empty Weight).

The cost metric preferred in this study is Cash Direct Operating Cost / Available Seat Mile (DOC/ASM), as defined and used in an earlier NASA study<sup>21</sup>. It has the advantage of being an operating cost metric that is quantifiable in design studies, offers a fair and ready comparison between aircraft, and is also relevant to the airline operator since their revenue is readily expressed in equivalent terms, (Revenue/ASM). Cash DOC is defined in Table 5.

**Table 5. Definition of Cash DOC**

OPERATING COSTS		
Cash DOC	<b>Direct Operating Cost (DOC)</b>	
	Fuel & Oil	
	Maintenance (Price)	
		Airframe, Labor & Parts
		Engine Restoration
		Dynamic Systems/Life Ltd
		Burden
	Landing Fees	
	Crew Expenses	
	Supplies-Catering	
	<b>Indirect (Fixed) Operating Cost</b>	
	Flight Crew	Salaries + benefits
	Cabin Crew	Salaries + benefits
	Hanger Costs	
	Hull Insurance	
	Depreciation	
	Financing	
	Training	
	Computer Mgt pgm	
	Refurbishment	

Mr. Neil Stromach, V.P. of Operations, Planning, Control & Reliability for Delta Airlines, gave a special presentation at the 2008 NASA Fundamental Aeronautics Program meeting<sup>22</sup>. In this illustrative presentation, he referred to “RASM” and “CASM”, the Revenue per available seat-mile and the Cost per available seat mile, respectively. The balance of these two metrics is a fundamental indicator of an

<sup>21</sup> Williams, R, Rosenstein, H, Wilkerson, J. "Advanced Vertical-Lift Configuration Studies"; Presented at the American Helicopter Society Powered Lift Forum 58, June 12, 2002, Montreal, Canada

<sup>22</sup> Neil Stromach, Plenary Speaker presentation, NASA Fundamental Aeronautics Program meeting , October 7, 2008, Atlanta, GA



airlines financial health, where revenue must be greater than cost to offset the indirect operating costs and to provide shareholder profit. It offers substantiation to the use of Cash DOC/ASM adopted in this study as a fundamental economic metric.

Table 6 summarizes the components of Cash DOC used in the study and their source. The ground rule utilization of 2500 flight hours per year actually required 2.5 flight crews and cabin crews per aircraft because they are limited to 1000 flight hours per year. The annual crew salaries from Conklin & deDecker were divided by 1000 to express them as \$/FH.

Some elements of Cash DOC/ASM were not supported by the version of PRICE used in ModelCenter. For instance, the aircraft fuel requirement depends on the rotorcraft concept, cruise altitude and speed, and of course varies considerably with the introduction of advanced technology. The cost of fuel and oil, flight crew salaries, cabin crew salaries, landing fees, crew expenses, and supplies and catering were added to the PRICE output with the Post-Price module in RCDA to arrive at Cash DOC/ASM.

**Table 6. Cash DOC/ASM: Component Source and Values**

O&S Element	Value or Basis	Source
Fuel & Oil	\$5.00 / gallon 3% of Fuel cost	Mission fuel from HESCOMP or VASCOMP
Maintenance	Calibration with adjustment for civil production and technology	PRICE
Landing Fees & Crew Expenses	≈ \$50 / FH	Conklin & deDecker Estimated
Supplies & Catering	\$8 for each Passenger & Crew	Estimate
Flight Crew Salaries*	\$204.75 / FH	Conklin & deDecker
Cabin Crew Salaries	\$82 / FH	Conklin & deDecker

Cash DOC/ASM can be expressed as shown below, clarifying the importance of cruise airspeed (or block speed) to this metric. The numerator is not very sensitive to airspeed, but the denominator increases directly with airspeed, thus driving down the DOC/ASM for higher block speeds.

$$\text{DOC/ASM} = \frac{\text{DOC/FH}}{\text{Number of seats} * \text{BlockSpeed (nm/hr)}}$$

Equally important, a higher block speed (airspeed) may allow the operator to get an extra short flight in the day for that aircraft, increasing its utilization. Large aircraft having more seats also receive a similar direct benefit by increasing the denominator. This is an economic benefit only up to the point where the aircraft capacity begins to exceed the route's market demand. Otherwise, all airlines would fly the B747 on all routes.

Figure 18 shows a sample of Cash DOC/ASM versus DOC/FH. Long range jet aircraft have the highest DOC/FH, they also have the lowest Cash DOC/ASM as a result of large passenger capacity and high cruise airspeed. It is a vivid reminder that slow flying aircraft with few seats cannot compete with turboprops against this metric, much less compete with large turbofan aircraft. The DOC/ASM of helicopters are very high.

Hence, this study pushed both airspeed and passenger size up to a range that would be more likely to produce an economically competitive civil rotorcraft.

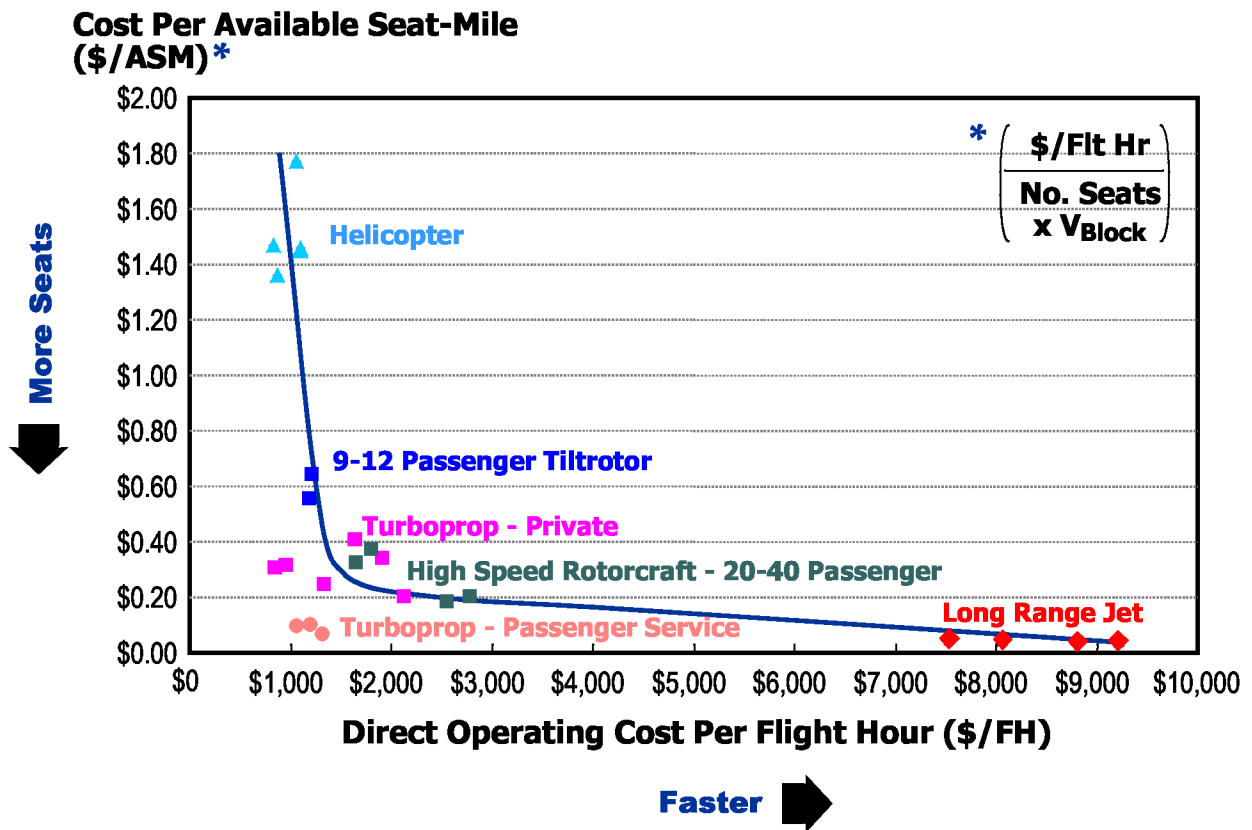


Figure 18. Representative Cash Direct Operating Costs

## **6. Rotorcraft Concept Descriptions**

### **6.1. Baseline Technology**

A few ground rules were established for technology levels applied to sizing the baseline civil rotorcraft. Generally, the aircraft size and performance were based on current, in-production technology for engines, drive systems, main rotors, airframe structure, parasite drag and hover download. These are listed below.

- Engines: AE1107C or GLC-38 turboshaft (up to Mach 0.8).
- Single-speed drive systems, where engines and rotors/propellers always have the same rpm ratio
- Rotor hover Figure of Merit and tip speed selected appropriate for SMRC and CTR.
- Aircraft component weight trends based on production CH-47 or V-22
- Fixed equipment weight scaled to the applicable passenger capacity, similar to turboprop or RJ.
- Aerodynamic cleanliness similar to clean helicopters (SMRC) or the F-27 (CTR)
- Hover download analysis based on experience with helicopters and tilt rotors.

### **6.2. Single Main Rotor Compound Helicopter**

#### **6.2.1. General Description of the SMRC Concept**

The SMRC helicopter configuration consists of a single main rotor, a lifting wing, and standard propellers on the wings for auxiliary propulsion in cruise. The engines and propeller nacelles are mounted at the wingtips with two engines and one propeller per nacelle. The engines are coupled through an interconnect cross shaft to the central main rotor transmission. This arrangement maintains power to the main rotor and both propellers in the event of a single or multiple engine failure, for all flight modes.

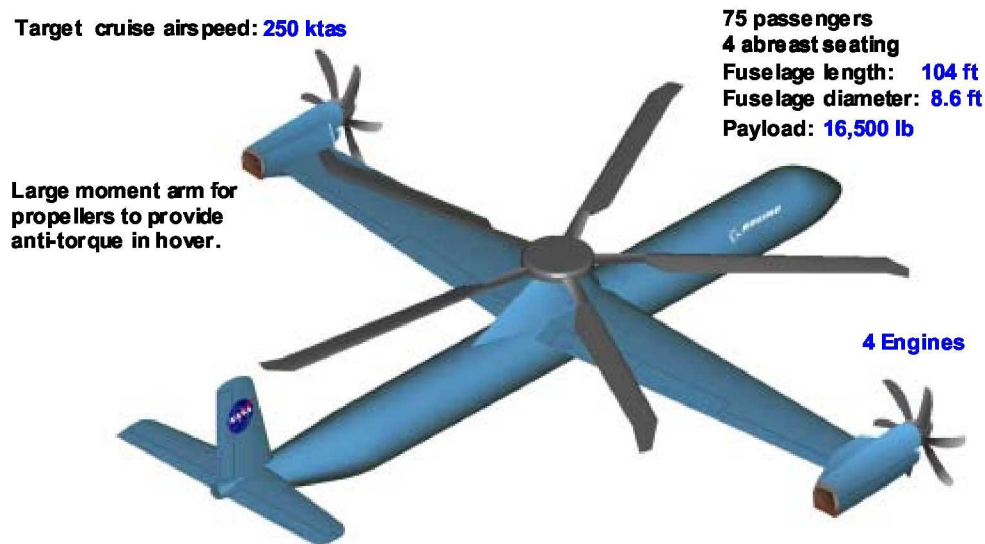
The 5-bladed main rotor has  $-5^\circ$  of linear twist, with a swept-tapered tip;  $30^\circ$  quarter-chord sweep and planform taper of 0.6 beginning at 0.92R. The rotor was sized to 15.0 lbs/ft<sup>2</sup> disc loading at Design Gross Weight (DGW), giving a main rotor diameter of 82.5 ft. Rotor solidity is 0.13 (thrust weighted). The hover tip speed is 650 ft/sec, and the rotor is slowed at high airspeeds to limit the advancing tip Mach number ( $M_{AT} \leq 0.81$ ), giving a 546 ft/sec tip speed at the design cruise condition.

The lifting wing carries approximately 90% of the aircraft weight at cruise airspeed, with the remaining 10% retained on the rotor. The propellers provide all the propulsive force required by the aircraft in cruise. Thus the rotor is producing relatively low lift ( $C_T/\sigma \approx 0.03$ ) and no propulsive force in cruise, and flapping is trimmed to near zero hub moments. Note that some engine power is provided to the rotor in this cruise state; thus the SMRC rotor does not auto-rotate like an autogiro rotor in cruise.

Anti-torque and yaw control in hover and low-airspeed flight are provided by the propellers mounted at the wing tips. The propellers have reverse thrust capability to generate a large anti-torque moment in hover. Rotor torque is low in cruise and may be trimmed by the vertical tail.

#### **6.2.2. Baseline Design**

The baseline SMRC helicopter concept is shown in Figure 19.



**Figure 19. Single Main Rotor Compound Helicopter Concept**

The engine specific fuel consumption (lbs/hr/HP) and lapse rate with altitude and temperature are based on the AE1107C turboshaft engine. The SMRC was designed with four engines to alleviate the penalty for the FAA Category A OEI takeoff requirement. Even so, the engines were sized by the OEI takeoff requirement, and have 20% more power available than required for the cruise condition.

At the design cruise airspeed of 250 ktas and 20,000' altitude, the propeller power is 83% of the total power required, operating at 0.85 propeller efficiency for the baseline technology. The engines, main rotor, and propellers are slowed to 84% rpm, for a rotor tip speed of 546 fps and advance ratio of 0.77. The main rotor chordwise tip Mach number is 0.808 in cruise at  $\Psi = 90^\circ$  with the assumed  $30^\circ$  tip sweep.

Main rotor hover performance is critical for the SMRC helicopter, since the OEI hover condition sized the engines. However, rotor vibratory loads at the high speed cruise condition are also very important. Therefore, the rotor could not be designed solely for the hover requirement, and the modest hover Figure of Merit of the baseline design rotor reflects the relatively low twist and high solidity chosen from considerations of reducing vibratory rotor loads at high speeds. The rotor blade design is described in Figure 20. At the design mission takeoff condition and gross weight, the rotor tip Mach number is 0.567, and the HOGE  $C_T/\sigma$  is 0.147 with a hover thrust/weight ratio of 1.14.

Hover performance was predicted using the rotor performance analysis code EHPIC, for the main rotor aerodynamic design. EHPIC runs were made before the rotor solidity was increased to 0.13 and the rotor diameter was smaller. However, since this performance is input to HESCOMP in  $C_T/\sigma$  tables, it is still representative of the design. Hover performance is shown in the Figure of Merit (FM) versus  $C_T/\sigma$  plot of Figure 21. The rotor Figure of Merit is 0.707 at the DGW.

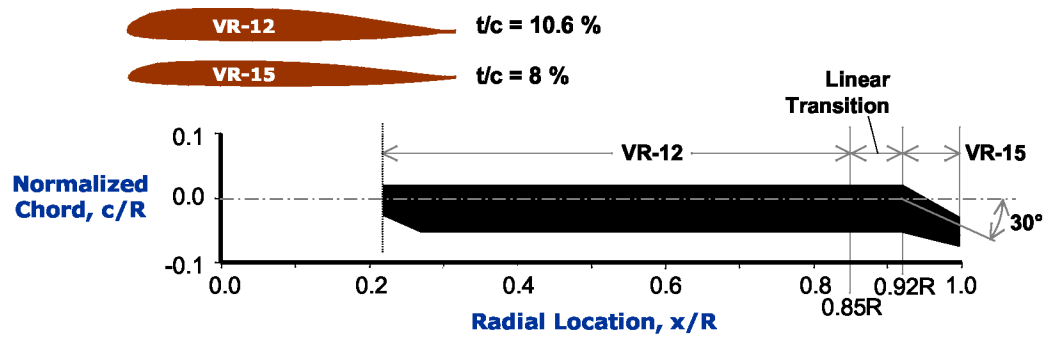


Figure 20. SMRC Helicopter Rotor Blade Design

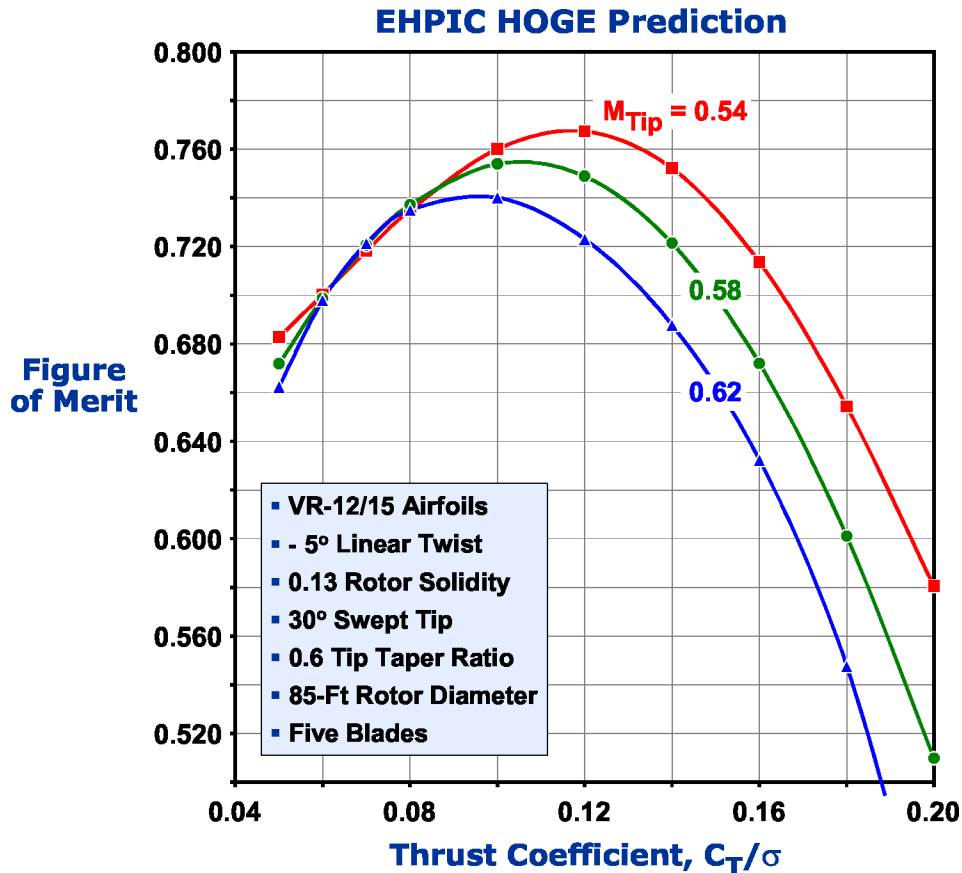


Figure 21. Predicted Hover Performance for the SMRC Baseline Rotor

Main rotor level flight performance was predicted using Boeing's rotor forward flight analysis code TECH-02. This performance is shown in the  $L/D_e$  versus  $\mu$  plots of Figure 22. These data were generated with rotor propulsive force set to zero in TECH-02, so it is accurate only for the high-speed compound helicopter design where the auxiliary propulsion provides all the propulsive force.

In cruise, the rotor is at an advance ratio of 0.77 and  $C_T/\sigma$  of  $\approx 0.03$ . Referring to the  $L/D_e$  curves in Figure 22, the rotor  $L/D_e$  is 4.84 at this cruise condition.

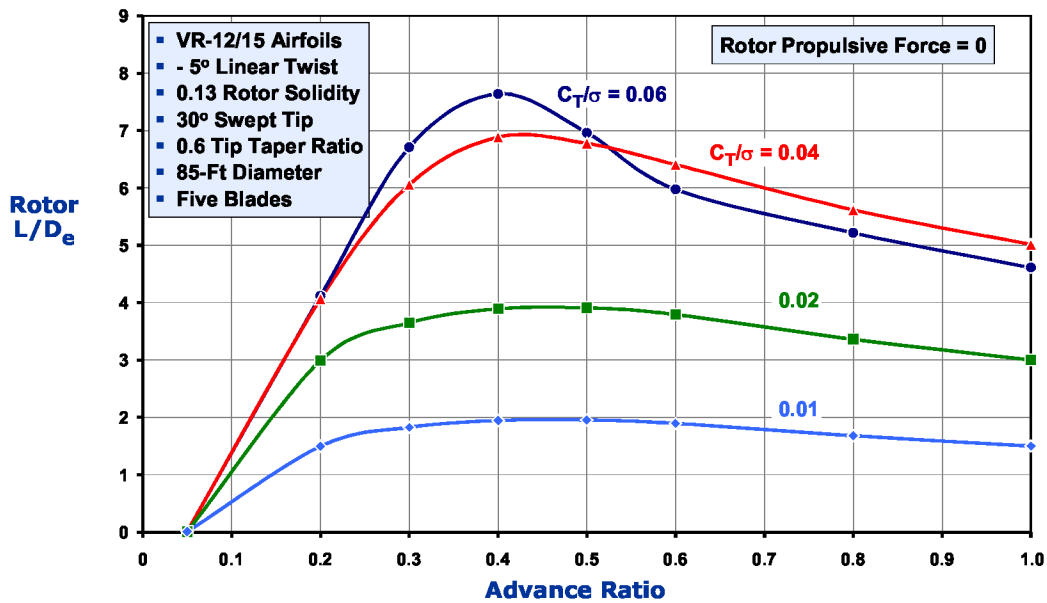


Figure 22. Predicted Cruise Performance for the SMRC Rotor

Rotor performance at low flight speed and higher  $C_T/\sigma$  are shown in Figure 23.

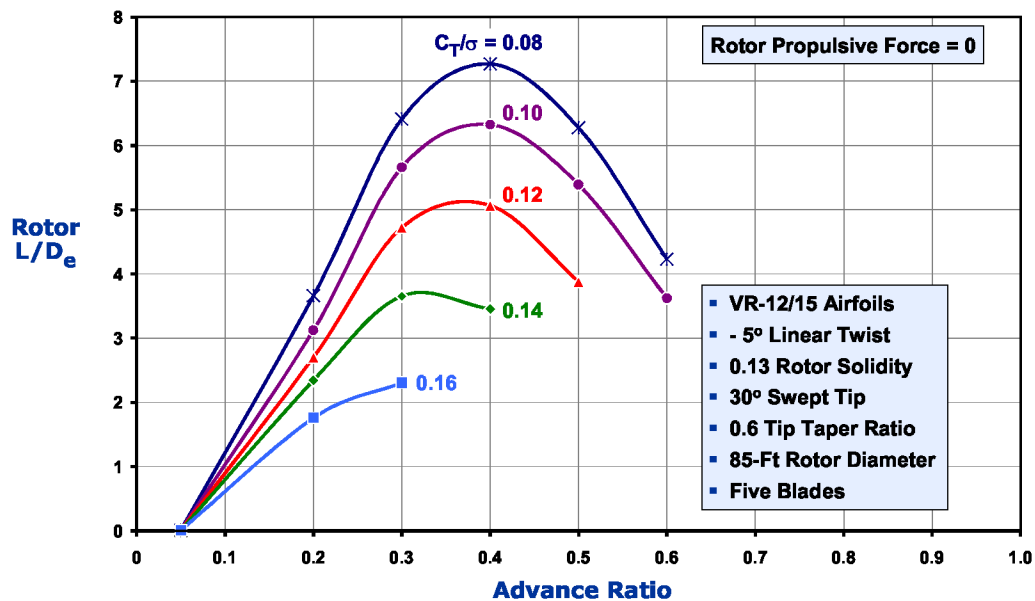
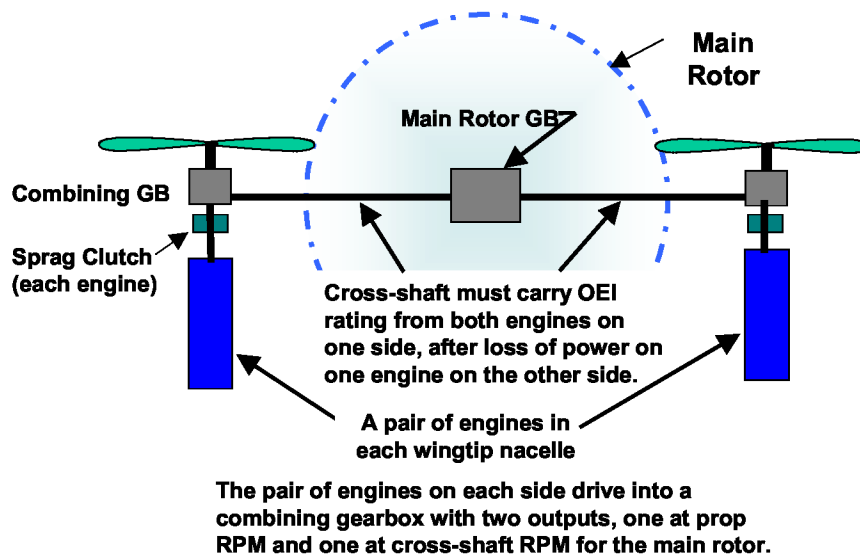


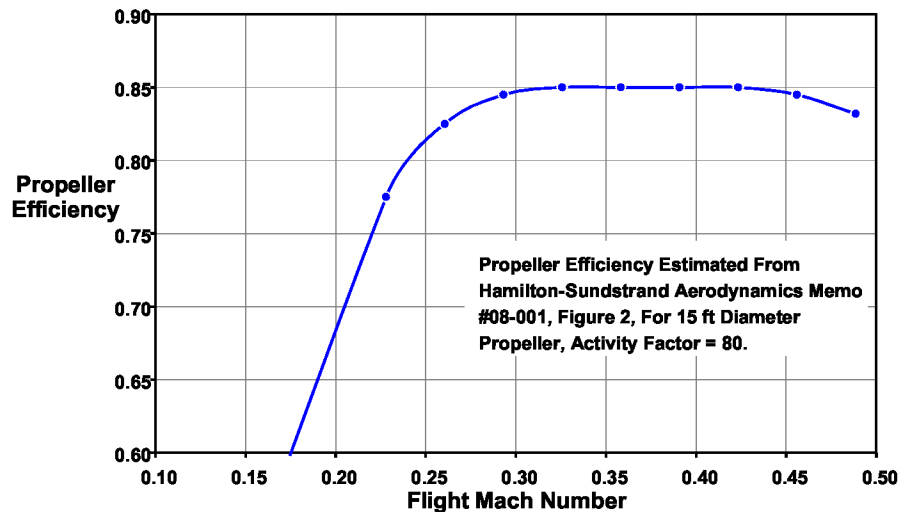
Figure 23. Predicted Low-Speed Performance of the SMRC Rotor (higher  $C_T/\sigma$ )

The SMRC drive system combines output from two engines (on each wing tip) to a combining gearbox. The output from that wingtip gearbox drives the propeller at its operating rpm and drives its interconnect cross-shaft at a higher rpm. The interconnect shaft from both wing tips provide power to the single main rotor transmission, as shown in Figure 24. The interconnect drive shafting is sized to handle the OEI power from both engines on one side when an engine is inoperative on the opposite side.



**Figure 24. SMRC Drive System Schematic**

Propeller performance was based on data from Hamilton-Sundstrand via a Proprietary Information Exchange Agreement (PIEA) with Boeing. Propeller efficiency for the SMRC is shown in Figure 25 versus flight Mach number.



**Figure 25. SMRC Propeller Efficiency Versus Flight Mach Number**

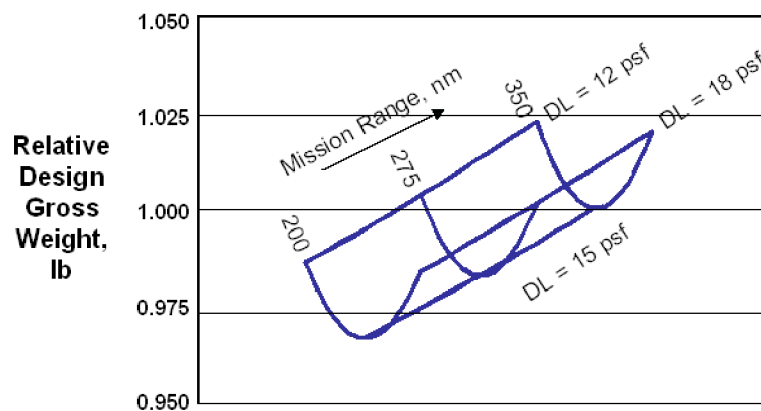
Discussions about this application for propellers indicated that today's propeller performance was near the limit of what could be achieved for the relatively low SMRC cruise speed of 250 ktas. Advanced propeller technology was not considered further for this application. While current advanced propellers, such as the NP2000, are breaking new ground in propeller design, those designs are optimized for more demanding flight conditions at cruise speeds upwards of 400 knots.

### 6.2.3. Design Space and Trade-offs

Early trade studies showed an almost linear variation of Gross Weight with increasing number of passenger seats. There was a modest, but clear benefit for 4-abreast seating, and a very small benefit with 5-abreast seating, but no definitive break in Gross Weight versus number of passengers.

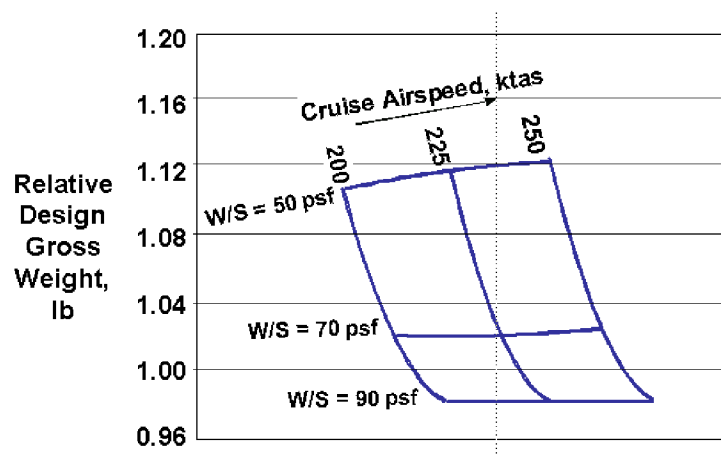
The SMRC cruise speed of 250 knots would easily cover a 350 nm range in a 1.5 hour flight, placing it in competition with the large turboprops, which to date have been limited to 50 passengers or less. A 75 passenger capacity was selected as reasonable for this concept, short of a thorough Operations Analysis.

Initial sizing studies were conducted to assess the impact of mission range, wing loading (W/S), disk loading (DL), and cruise airspeed on the SMRC concept design gross weight (DGW). Naturally, not all inputs were finalized during these initial studies, so relative DGW is shown in the following two charts. Figure 26 shows a relative minima in DGW at DL= 15 psf, but DGW continued to rise with mission range, as expected.



**Figure 26. Baseline SMRC DGW Trade-off With Range and Disk Loading**

Design Gross Weight was relatively insensitive to the cruise airspeed, as shown in Figure 27. That reflects the fact that installed SHP and transmission rating were determined by the hover condition, and airspeed was a fallout. However, the design was clearly sensitive to the wing loading (W/S). So the two most sensitive parameters were W/S and mission range, accepting 15 psf as the best choice for DL.



**Figure 27. Baseline SMRC DGW Trade-off with Wing Loading and Airspeed**



The sensitivity of DOC/ASM to W/S and airspeed identified a relative minimum between 225 and 250 knots, and was less at higher W/S, up to 90 psf as shown in Figure 28. Later sizing cases showed W/S of 80 psf was preferred for cruise at 20,000' altitude.

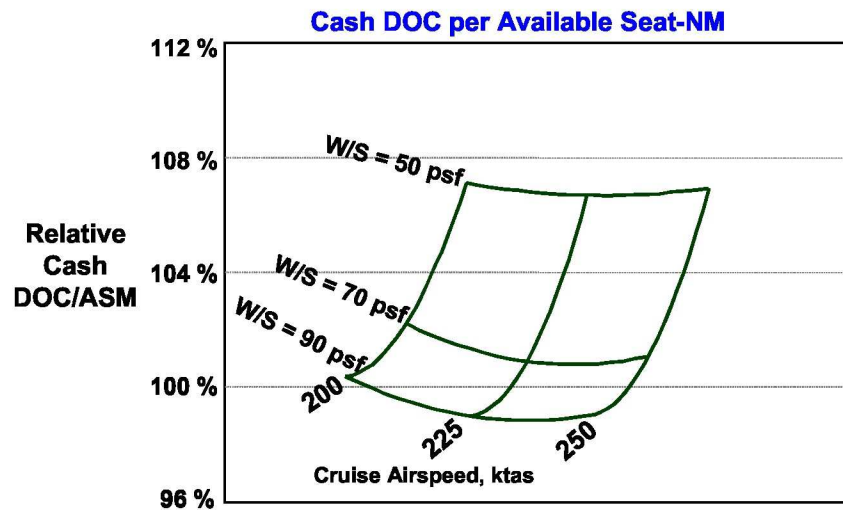


Figure 28. Baseline SMRC DOC/ASM Trade-off with Wing Loading and Airspeed

#### 6.2.4. SMRC Baseline Design

The final SMRC baseline design is shown in Figure 29, selected on the basis of the trade-offs shown above.

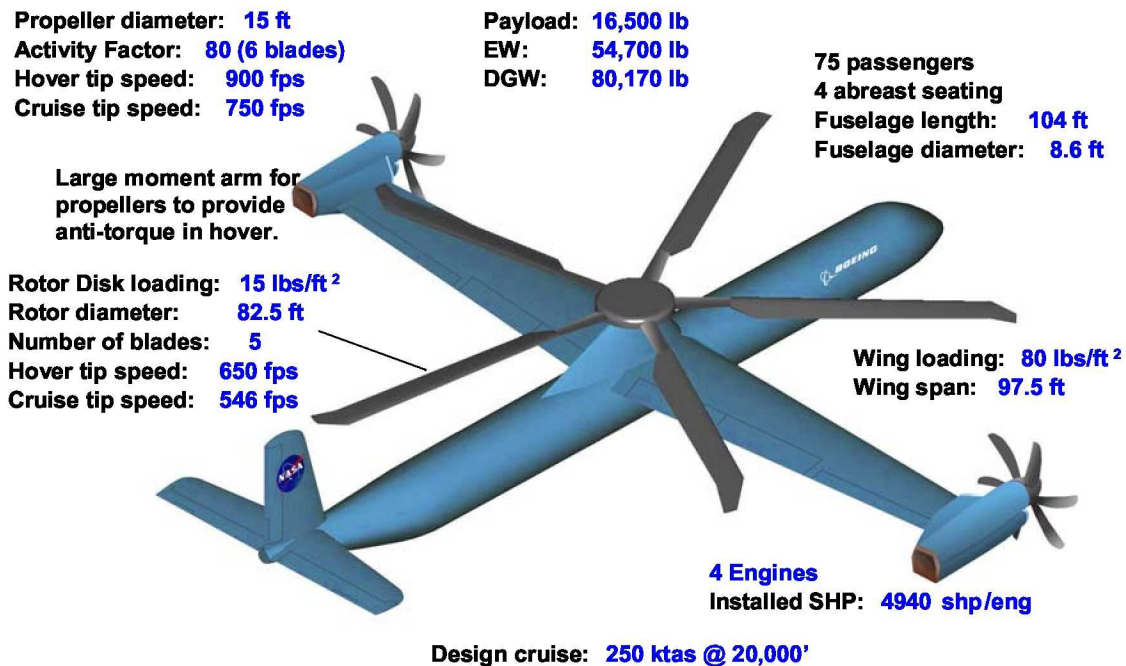


Figure 29. Final SMRC Helicopter Baseline Design

Main attributes of the baseline SMRC are summarized in Table 7.

**Table 7. Attributes of Baseline SMRC**

<b>Attribute</b>	<b>Value</b>
Design Gross Weight	80,170 lb
Empty Weight	54,700 lb
Mission Fuel	7460 lb
Installed SHP (SLS, Static)	4940 SHP/ Eng
Number of Engines	4
Wing Loading	80 psf
Wing Area	1002 sq.ft.
Aspect Ratio	9.5
Wing Span	97.5 ft
Rotor Disk Loading	15 psf
Diameter	82.5 ft
Number of Blades	5
Solidity	0.13
Tip Speed – Hover	650 fps
– Cruise	546 fps
Fuselage Diameter	8.6 ft
Number of Passenger Seats	75
Number of Seats Abreast	4
Fuselage Length	104 ft
Propeller Diameter	15 ft
Number of Propellers	2
Number of Propeller Blades	6

Details of the baseline SMRC drive system rpm and ratings are:.

- Hover
  - Engine shaft output RPM 12,000
  - Propeller shaft RPM (Vtip=900 fps) 1,146
  - Cross-shafts to main transmission RPM 6,944
  - Main rotor shaft RPM (Vtip=650 fps) 150.5
- Cruise
  - Engine shaft output RPM 10,080
  - Propeller shaft RPM (Vtip=756 fps) 963
  - Cross-shafts to main transmission RPM 5,833
  - Main rotor shaft RPM (Vtip=546 fps) 126.4
- Main Rotor transmission rating 15,604 HP
- Combining gearbox max propeller output 3,218 HP
- Combining gearbox max cross-shaft output 9,360 HP

Table 8 shows the baseline SMRC weight breakdown.

**Table 8. Baseline SMRC Weight Breakdown**

H E S C O M P  
HELICOPTER SIZING & PERFORMANCE COMPUTER PROGRAM      B-91

MLF	MANEUVER LOAD FACTOR	2.500	
GLF	GUST LOAD FACTOR	2.436	
ULF	ULTIMATE LOAD FACTOR	3.750	
PROPULSION GROUP			20617.
	WPRG	TOTAL MAIN ROTOR GROUP	6981.
SKPRBAF K12	WPRB	MAIN ROTOR BLADES (PER ROTOR)	4331.
K13	WPH	MAIN ROTOR HUB (PER ROTOR)	2650.
K21	WBF	BLADE FOLDING (PER ROTOR)	0.
K15	WAR	AUXILIARY PROPULSION ROTOR GROUP	928.
	WDS	DRIVE SYSTEM	8109.
K16	WPDS	MAIN ROTOR DRIVE SYSTEM	7241.
K20	WTRDS	TAIL ROTOR DRIVE SYSTEM	0.
K17	WADS	AUXILIARY PROPULSION DRIVE SYSTEM	868.
K18	WEP	PRIMARY ENGINES	3161.
	WPEI	PRIMARY ENGINE INSTALLATION	319.
	WFS	FUEL SYSTEM	1119.
	DELWP	PROPULSION GROUP WEIGHT INCREMENT	0.
STRUCTURES GROUP			21621.
K8	WW	WING	7713.
	WTG	TAIL GROUP	924.
K9	WHT	HOR. TAIL	634.
	WVT	VERT. TAIL	290.
K14	WTR	TAIL ROTOR	0.
K6	WB	FUSELAGE	9457.
K7	WLG	LANDING GEAR	2891.
	WNG	NOSE GEAR	578.
	WMG	MAIN GEAR	2313.
	WTES	TOTAL ENGINE SECTION	139.
	WPES	PRIMARY ENGINE SECTION	139.
	DELTA WST	STRUCTURE WEIGHT INCREMENT	497.
FLIGHT CONTROLS GROUP			2507.
	WPFC	PRIMARY FLIGHT CONTROLS	2294.
	WCC	COCKPIT CONTROLS	186.
K1	WRC	MAIN ROTOR CONTROLS	874.
K2	WSC	MAIN ROTOR SYSTEMS CONTROLS	994.
K3	WFW	FIXED WING CONTROLS	241.
	WSAS	SAS	0.
	WAFC	AUXILIARY FLIGHT CONTROLS	212.
K4	WRCA	AUX. PROPULSION ROTOR CONTROLS	38.
K5	WSCA	AUX. PROPULSION ROTOR SYS. CONTROLS	174.
WFE		WEIGHT OF FIXED EQUIPMENT	9959.
			--
WE		WEIGHT EMPTY	54704.
WFUL		FIXED USEFUL LOAD	1506.
WPL		PAYLOAD	16500.
(WF)A		FUEL	7459.
			-----
WG		GROSS WEIGHT	80169.

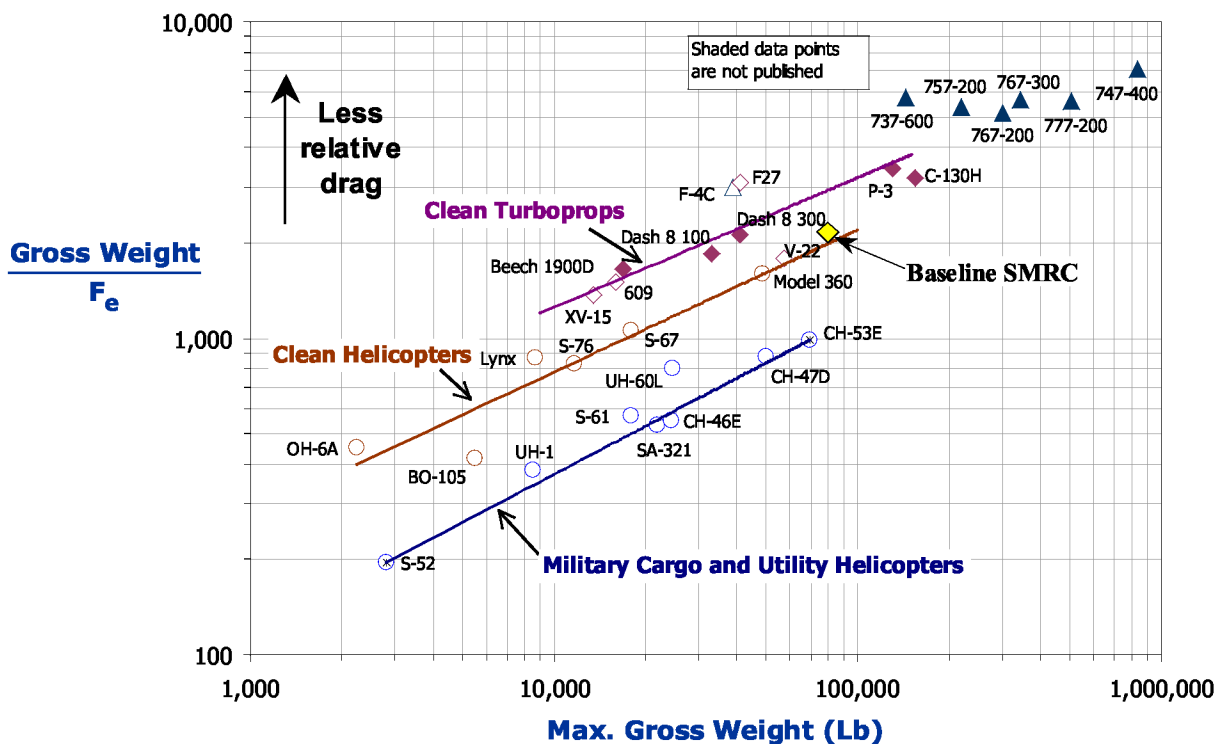
### 6.2.5. General Performance

The baseline SMRC helicopter is a clean rotorcraft design. Table 9 shows the equivalent flat plate area (fe) drag breakdown, with the hub and rotor pylon contributing 49 % of the total equivalent flat plate area.

**Table 9. Baseline SMRC Parasite Drag Breakdown**

Drag Component	Equivalent Flat Plate Area (ft <sup>2</sup> )
Fuselage	6.8
Main Rotor Pylon	3.4
Main Rotor Hub	15.4
Wing	7.8
Empennage	2.6
Engine/Prop nacelles	2.4
<b>Total fe</b>	<b>38.4</b>

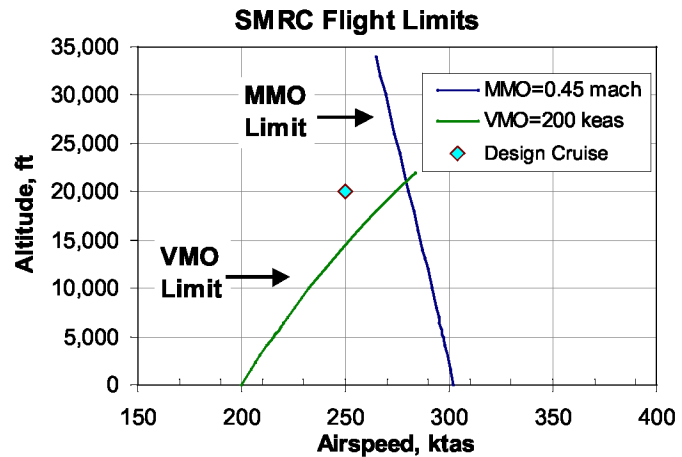
The baseline SMRC has a higher fe than the V-22, as expected of a larger aircraft, with a larger fuselage and a wing area about 2 ½ times that of the V-22. But the estimated parasite drag compares well with other clean helicopters when expressed in terms of GW/fe over a range of aircraft gross weight, as shown in Figure 30.



**Figure 30. Equivalent Drag of the Baseline SMRC**

The flight envelope is limited by the selected maximum operating airspeed (VMO, keas) and maximum operating Mach number (MMO), and the power and transmission limits. The VMO and MMO limits with altitude are shown in Figure 31.

**Figure 31. SMRC Flight Limits**



## 6.3. Civil Tilt Rotor

### 6.3.1. General Description of the CTR Concept

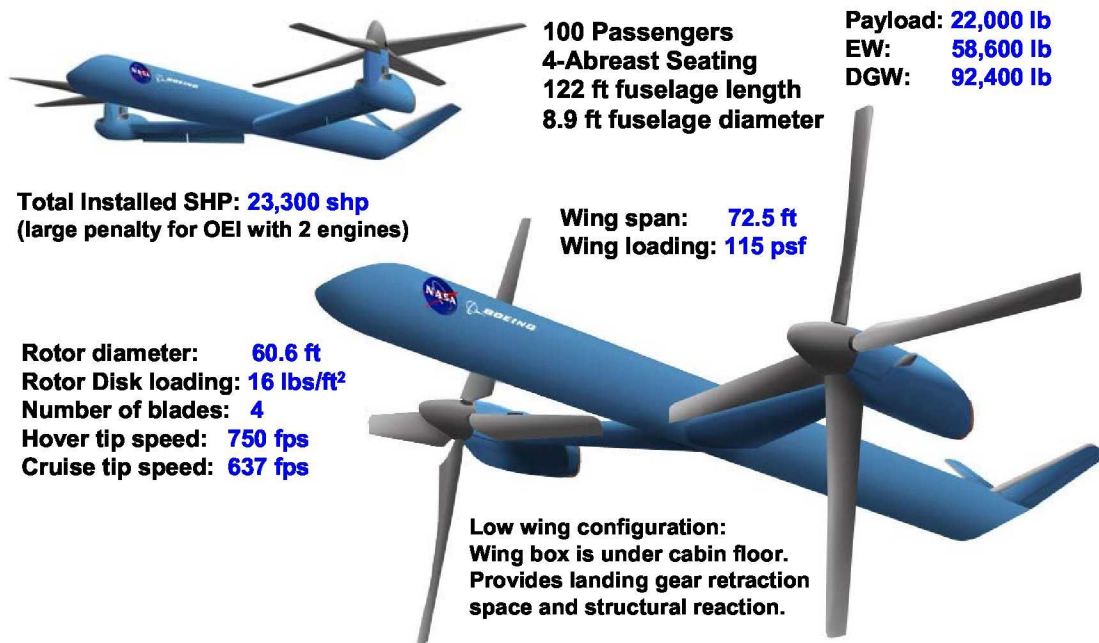
The purpose of this study was to evaluate the influx of advanced technologies on the ability of civil rotorcraft to effectively reduce airport congestion and increase passenger throughput. It was not to develop an advanced configuration. Hence, the selected Civil Tilt Rotor concept is similar to that of previous studies of CTR aircraft. As previously described, the CTR aircraft was sized to accommodate 100 passenger seats. A low-wing configuration with non-tilting engines was selected, shown in Figure 32, with a single-speed drive system so the engine rpm reduces in cruise flight with the rotor rpm..

The low wing offers the same advantages seen in current turbofan airliners, that is an efficient structural path from the landing gear into the large center wing box structure and a convenient location for landing gear retraction in the wing. The low wing passes below the cabin floor, avoiding spatial interference with the passenger headroom of a high wing configuration.

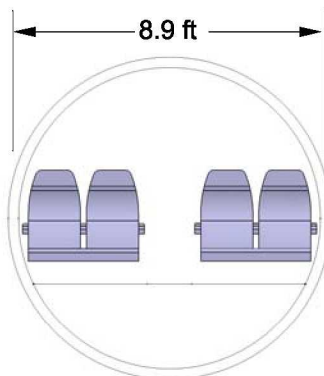
The low wing arrangement for a tilt rotor requires non-tilting engines. The proximity of hot jet exhaust of a tilting engine could damage the tarmac and exacerbate the ground wash for ground crews in the vicinity of the aircraft as it taxied into or out of the terminal.

A four-bladed rotor was chosen as a reasonable baseline, prior to evaluating any acoustic analysis.

Four abreast, single-aisle seating was selected with a 8.9 ft fuselage diameter, shown in Figure 33 and Figure 34, similar to several Region Jet configurations such as the CRJ900. A pure circular cross-section with 4-abreast seats does not provide space for under floor baggage space. The usable depth below the cabin floor is about 26 inches, after accounting for depth of the floor beam and providing a flat surface for baggage, which is too small to accommodate baggage for 100 passengers.

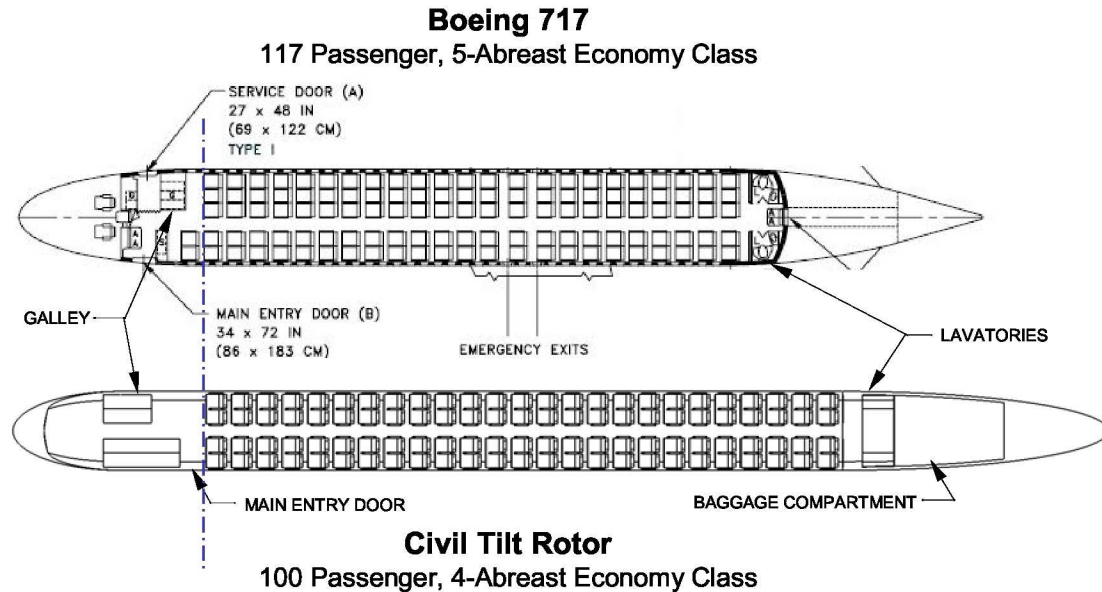


**Figure 32. Civil Tilt Rotor Configuration**



**Figure 33. CTR Cross Section for 4-Abreast Seating**

A baggage compartment was therefore provided on the passenger level, with two lavatories and a galley. This resulted in a long fuselage with 25 seat rows for the 100 passenger CTR. A comparison of the CTR interior arrangement to the Boeing 717 is shown in Figure 34. The images have been adjusted to approximately the same seat width and aisle width with the first full row of seats aligned for comparison. An optimization of the CTR cabin width (seats abreast) may have resulted in a shorter 5-abreast configuration. But a cursory examination showed little difference in empty weight between 4-abreast and 5-abreast.



**Figure 34. Interior Arrangement for 100 Seat CTR and Boeing 717**

### 6.3.2. Baseline Technology

The baseline CTR assumed current technology across the board, much of it referenced to the V-22. This included engine performance, rotor performance and component weight trends.

The baseline engine performance was modeled from a GLC-38 with operating characteristics up to 0.8 Mach, representing a current production engine. The existing VASCOMP engine deck was calibrated to the AE1107C specific fuel consumption,  $SFC=0.408$  lbs/HP/hr at SLS, max takeoff power, to be representative of, current performance. The engine was allowed to scale to the size required during the CTR studies. Both 3 and 4 engines were evaluated.

Airframe parasite drag was estimated using the Boeing rotorcraft legacy drag analysis, Gabriel. The drag was updated after the baseline geometry was finalized to verify the estimate. A breakdown of the baseline drag is shown in Table 10 as equivalent flat plate area (fe).

**Table 10. Baseline CTR Parasite Drag Breakdown**

Drag Component	Equivalent Flat Plate Area (ft <sup>2</sup> )
Discrete Roughness	1.0
Fuselage	10.0
Wing	10.8
Empennage	2.4
Engine/Rotor nacelles	3.7
AC, Momentum, & Trim drag	1.2
Subtotal	28.1
Excrescence Factor (multiplier)	1.07
<b>Total fe</b>	<b>30.07</b>



Figure 35 shows the CTR parasite drag as GW/equivalent flat plate area (GW/fe) relative to other aircraft, including the baseline SMRC. The baseline CTR falls squarely on the trend line for clean turboprops. The SMRC is estimated to have slightly less drag than clean helicopters, due mainly to the lack of drag from devices such as tail rotors, large engine clusters on the body, or large aft pylons such as on a tandem rotor helicopter.

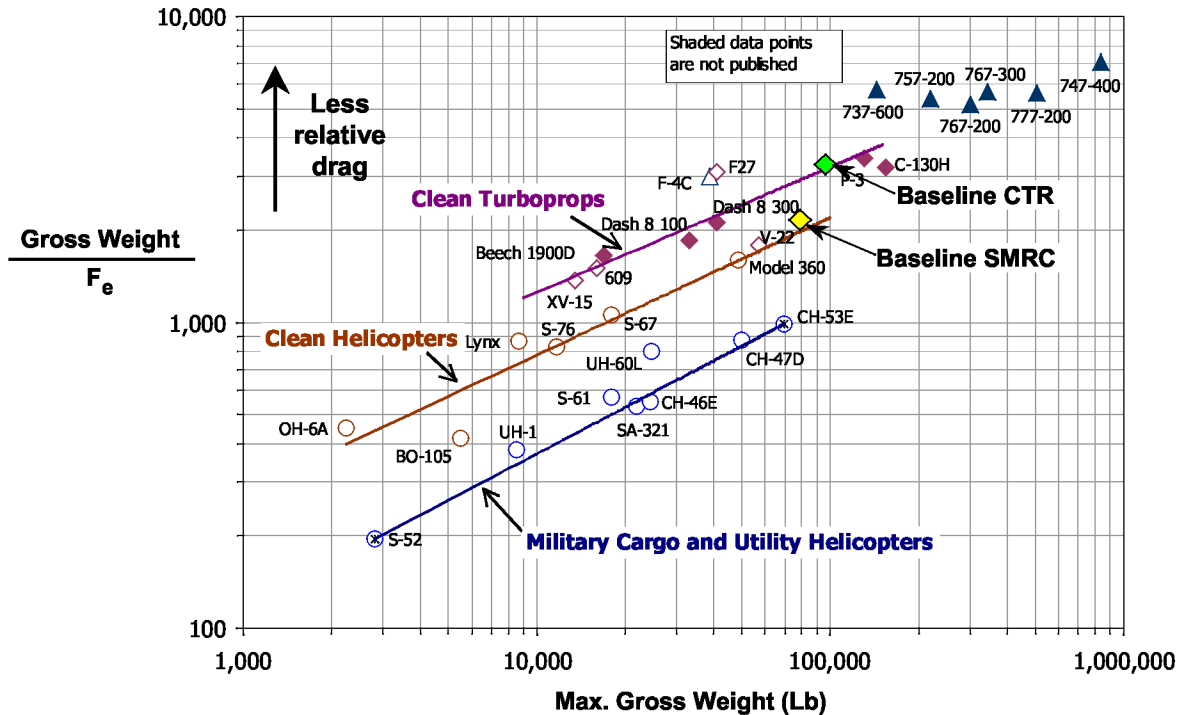


Figure 35. Drag of the Baseline CTR and SMRC Configurations

Total drag in cruise was the sum of flat plate area, induced drag, and drag due to compressibility. VASCOMP calculates induced drag for each climb and cruise segment with the standard formula ( $C_L^2 / \pi * e * AR$ ). Drag due to compressibility is a tabular function of Mach number and  $C_L$ , in this case based on the V-22 23% thick wing. The resultant aircraft lift/drag ratio and specific range variation with cruise airspeed for the baseline CTR are shown in Figure 36 at the design cruise altitude of 24,000 ft.

Performance of the baseline 4-blade rotor was based on the V-22 prop rotor airfoils and planform. Rotor tip speed was 750 fps in hover, reduced to 637 fps in cruise. Blade twist was adjusted for the target airspeed at 637 fps tip speed, at the design cruise advance ratio ( $\mu = 305 \text{ kts} * 1.689 / 637 \text{ fps} = 0.809$ ).

Rotor solidity was set by  $C_t / \sigma = 0.145$  at the takeoff DGW, 2,000 ft / ISA+20°C and a hover thrust/weight ratio of 1.103. Calculated performance for the baseline rotor in hover and in cruise are:

- Hover Figure of Merit = 0.738 at  $C_t / \sigma = 0.145$ , 2,000 ft / ISA+20°C,  $V_{tip} = 750 \text{ fps}$
- Cruise propulsive efficiency = 0.808 at 305 kts, 24,000 ft / ISA,  $V_{tip} = 637 \text{ fps}$



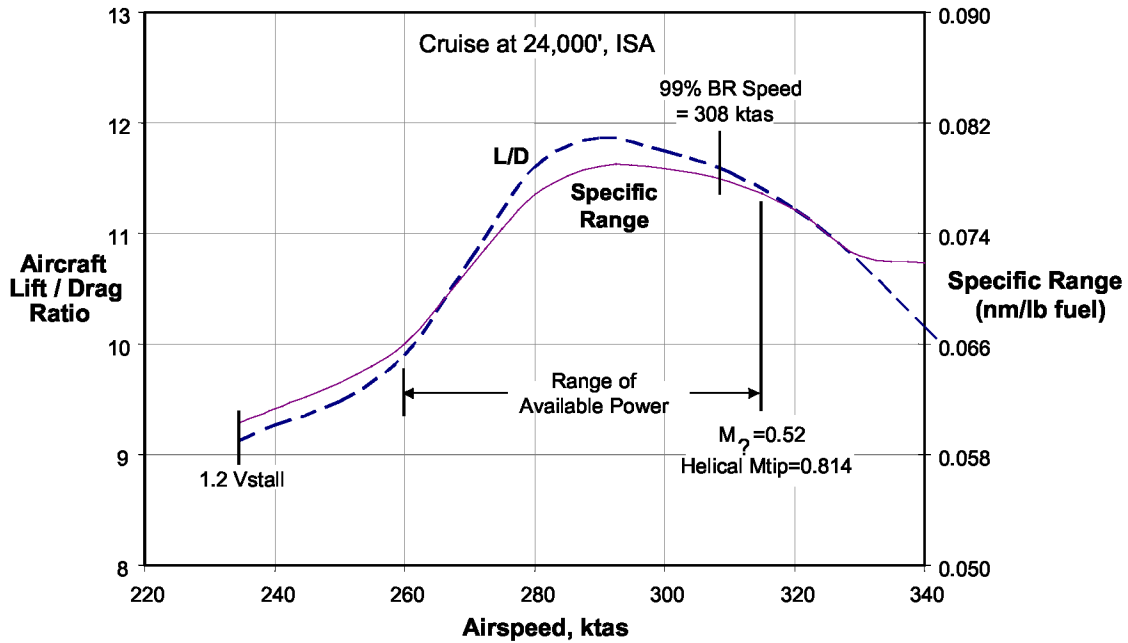


Figure 36. Baseline CTR Cruise L/D and Specific Range

### 6.3.3. Design Space and Trade-offs

The number of engines on the baseline aircraft design was driven by the need to satisfy FAA Category A one-engine-inoperative (OEI) criteria. Piloted simulations conducted during previous tilt rotor programs had determined that an OEI power of 92% of hover power is a satisfactory rule-of-thumb to execute a successful recovery from an OEI condition by FAA criteria. This can be satisfied by having more engines, by over-sizing the engines, by an assumed contingency rating, or by some combination of those three factors. The contingency rating is the ratio of emergency power available to the normal max takeoff power available. The following equation represents that relationship, where “Installed SHP” includes any engine over-sizing.

$$\text{OEI BHP} = 0.92 * \text{HOGE HP} = \text{Installed SHP} * \text{Contingency Rating} * \frac{(n-1)}{n}$$

or

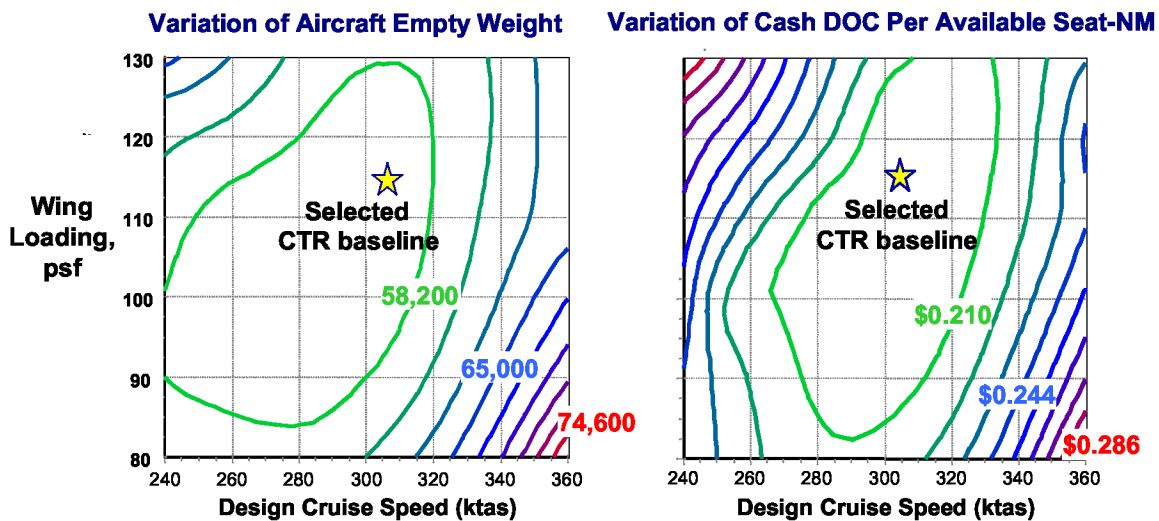
$$\frac{\text{Installed SHP}}{\text{HOGE HP}} = \frac{n}{(n-1)} \left( \frac{0.92}{\text{Contingency Rating}} \right)$$

Table 11 summarizes several sizing cases conducted to quantify the overall effect of number of engines. Two engines would require an additional 84% installed BHP than that required to hover out-of-ground-effect (HOGE) to satisfy the OEI criteria. But a 15% contingency was assumed, reducing the penalty to 60%. Three engines needed only 38% more power for OEI, and four engines needed only 23% more installed power. The consequence on the aircraft Gross Weight was artificially minimized for the two engine case by assuming a large contingency rating at no cost in fuel flow or engine weight. The 3 and 4 engine cases assumed no contingency rating. Note that installed power for the four engine case was determined by cruise, not by hover, so there would be no OEI penalty for a four-engine arrangement. This break-point for cruise versus hover sizing would change with other design parameters such as ambient hover conditions, design speed, cruise altitude, and cruise efficiency.

**Table 11. Consequence of Number of Engines**

Number of Engines	Contingency Rating	Sized by Hover or Cruise	Required SHP / HOGE BHP	Installed SHP / HOGE BHP	Relative GW
2	1.15	Hover	1.84	1.60	1.000
3	1.00	Hover	1.38	1.38	0.979
4	1.00	Cruise	1.23	1.23	0.973

Trade-offs were performed to determine the best combinations of cruise altitude, airspeed, wing loading and disk loading. The best altitude for cruise was determined to be about 24,000'. The best region for wing loading (W/S) and cruise airspeed at that altitude was identified from the contour plots of .Figure 37. Empty weight and Cash DOC/ASM showed similar areas for the best design space. An optimization would identify the best design point, but a W/S of 115 psf and cruise airspeed of 305 ktas were selected as satisfactory starting points for the baseline design.



**Figure 37. Carpet Plot of CTR Empty Weight and \$DOC/ASM With Wing Loading and Airspeed**

The effect of rotor disk loading and mission range on \$DOC/ASM were also evaluated to identify the most desirable combinations. Figure 38 shows lower disk loadings and longer mission range yield desired reductions in Cash DOC/ASM. A disk loading of 16 was selected for the baseline CTR, and the 600 nm mission range that was shown to be competitive in the initial comparison with turboprops (see Figure 10).

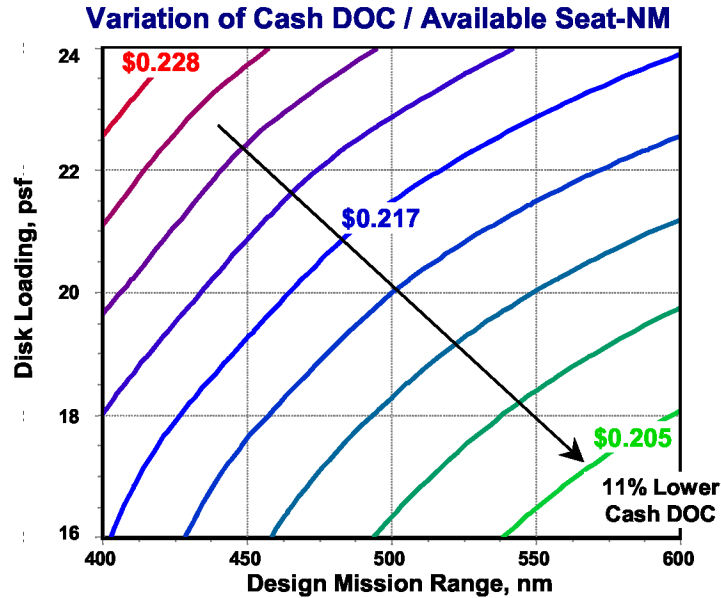


Figure 38. Effect of Disk Loading and Range on CTR Cash DOC/ASM

#### 6.3.4. Selected Baseline Design

The Civil Tilt Rotor was sized to carry 100 passengers over a 600 nm mission range with applicable FAA requirements for alternate destination (50 nm) and IFR reserve fuel (30 minutes). The primary features of the baseline CTR are listed below.

- Low wing configuration: provides efficient structure for load carry through and area for landing gear retraction
- Non-tilting engines: avoids hot jet exhaust on tarmac and onto nearby ground crews.
- Engines sized to the greater of Category A OEI with 15% contingency HP, or cruise power required.
- 4-bladed rotors
- 25 rows of 4-abreast cabin seating
- Baggage, galley and lavatories on cabin deck (no under belly cargo space)
- Wing loading and disk loading selected for best DOC/ASM
- Rotor solidity sized by hover.
- Rotor twist adjusted for cruise advance ratio.
- Rotor planform and airfoils from reference MV-22 technology.
- Rotor hover tip speed = 750 fps
- Engine and rotor cruise RPM = 85% hover rpm

Table 12 shows the weight breakdown for the baseline CTR.

**Table 12. Baseline CTR Weight Breakdown**

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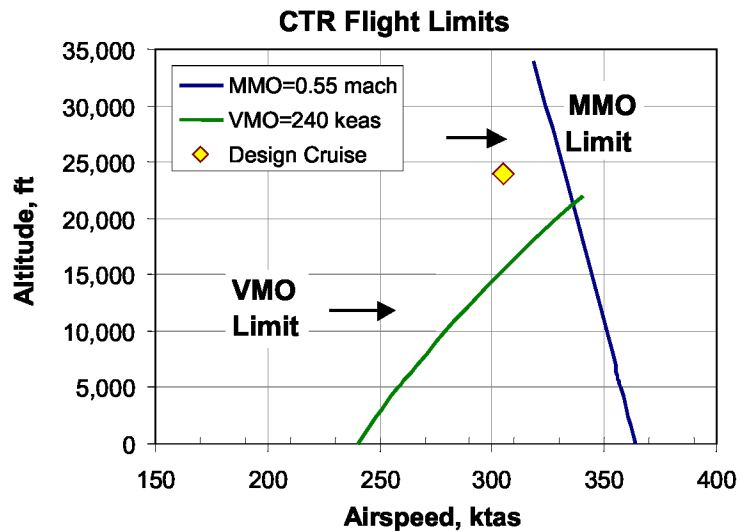
EMLF	MANEUVER LOAD FACTOR	2.500
GLF	GUST LOAD FACTOR	1.848
ULF	ULTIMATE LOAD FACTOR	3.750
GROUP WEIGHT STATEMENT PER MIL STD 1374A PART1		
STRUCTURE GROUP		29777.
WING GROUP	7221.	
ROTOR GROUP	8295.	
	(BLADE WT/ROTOR= 2242.)	
	(HUB WT/ROTOR = 1905.)	
	(FOLD WT/ROTOR = 0.)	
TAIL GROUP	860.	
	HORIZONTAL TAIL 860.	
	VERTICAL TAIL 0.	
BODY GROUP	8136.	
ALIGHTING GEAR GROUP	1405.	
ENGINE SECTION	3248.	
	PRIMARY ENGINE 3248.	
	LIFT ENGINE 0.	
STRUCTURAL WEIGHT INCREMENT	611.	
PROPULSION GROUP		12752.
PRIMARY ENGINE INSTALLATION	3455.	
PRIMARY ENGINE SYSTEMS	1037.	
LIFT ENGINE INSTALLATION	0.	
LIFT ENGINE SYSTEMS	0.	
FUEL SYSTEM	303.	
DRIVE SYSTEM	7957.	
PROPULSION WEIGHT INCREMENT	0.	
FLIGHT CONTROLS		3620.
COCKPIT CONTROLS	166.	
UPPER CONTROLS	1605.	
HYDRAULICS	0.	
FIXED WING CONTROLS	1387.	
STABILITY AUGMENTATION SYSTEM	0.	
TILT MECHANISM	462.	
CONTROLS WEIGHT INCREMENT	0.	
FIXED EQUIPMENT		12491.
CONTINGENCY		0.
		-----
TOTAL WEIGHT EMPTY		58640.
FIXED USEFUL LOAD		1716.
PAYLOAD		22000.
FUEL (wfa)		10086.
	FUEL IN WING(s) 10086.	
	FUEL IN BODY 0.	
		-----
GROSS WEIGHT		92443.

Physical attributes of the baseline CTR design are summarized in Table 13. Additional concepts for the CTR include neutral directional stability in airplane mode and the use of rotor cyclic pitch to aid pitch control in airplane mode, although neither of these were quantified in this study.

**Table 13. Attributes of Baseline CTR**

Attribute	Value
Design Gross Weight	92,440 lb
Empty Weight	58,640 lb
Installed SHP Number of Engines	7,757 SHP/ Eng 3
Wing Loading	115 psf
Wing Area	804 sq.ft.
Aspect Ratio	6.5
Wing Span	72.5 ft
Wing t/c	0.23
Rotor Disk Loading	16 psf
Diameter	60.6 ft
Number of Blades	4
Solidity	0.103
Tip Speed – Hover	750 fps
– Cruise	637 fps
Fuselage Diameter	8.9 ft
Number of Seats	100
Number of Seats Abreast	4
Fuselage Length	122 ft

The CTR flight limits of maximum operating airspeed (VMO, KEAS) and maximum operating Mach number (MMO) are shown in Figure 39.



**Figure 39. CTR Flight Limits**

## 7. Sensitivity to Key Parameters

A first step toward identifying and quantifying advanced technologies was to determine the relative sensitivity of the two baseline civil rotorcraft to changes in weight, performance, and engine fuel flow. Performance and component weights were perturbed from each concept's baseline design and the rotorcraft resized to quantify the rotorcrafts' sensitivity. The most effective advanced technologies were identified by that mean. Obviously, technical areas with more response (higher sensitivity) are good candidate areas for advanced technologies.

The magnitude of the perturbations were selected to be feasible and achievable, so there was a degree of judgment involved. Only the relative results were of interest, to determine the relative benefit of the technical areas. Table 14 shows the perturbation value for each component in three technical areas. The rotorcraft were resized for each perturbation and new cost estimates were generated.

**Table 14. Technologies Applied for Aircraft Sensitivity**

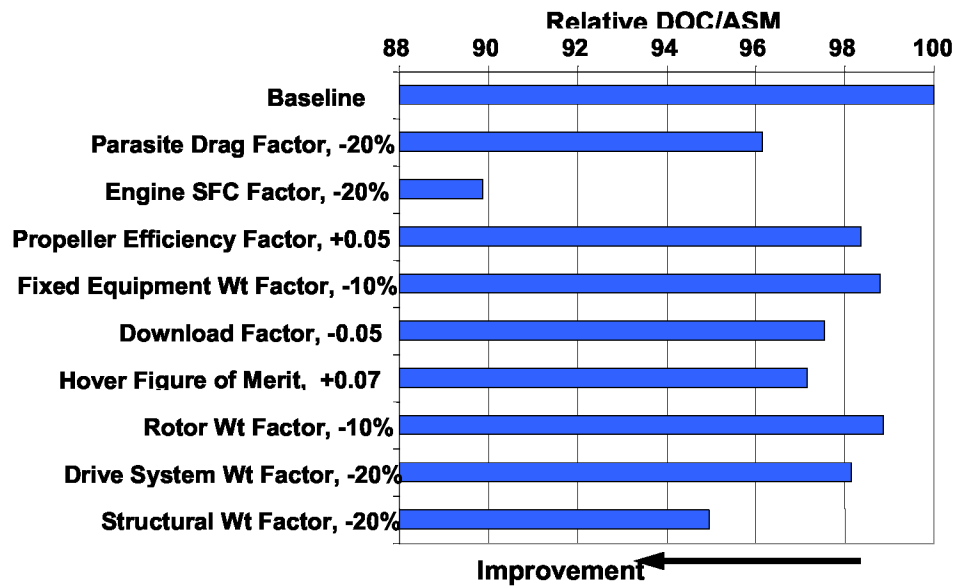
Technical Area	Component	Perturbation Value
<b>Weight</b>	Structure	-20 %
	Drive System	-20 %
	Rotor	-10 %
	Fixed Equipment	-10 %
<b>Performance</b>	Rotor Hover Figure of Merit	+0.07
	Rotor Cruise Propulsive Efficiency	+0.05
	Rotor Hover Tip Speed	-10%
	Propeller Cruise Efficiency	0
	Hover Download	-0.05
	Parasite Drag	-20 %
	Wing thickness ratio (profile & compressibility drag)	-0.02
<b>Propulsion</b>	Engine SFC	-20 %
	Cost of Fuel	- \$1 / gal

### 7.1. Single Main Rotor Compound Helicopter Sensitivity

The SMRC helicopter engines were sized by the hover condition, not by cruise. So the SMRC helicopter was more sensitive to hover performance than the CTR.

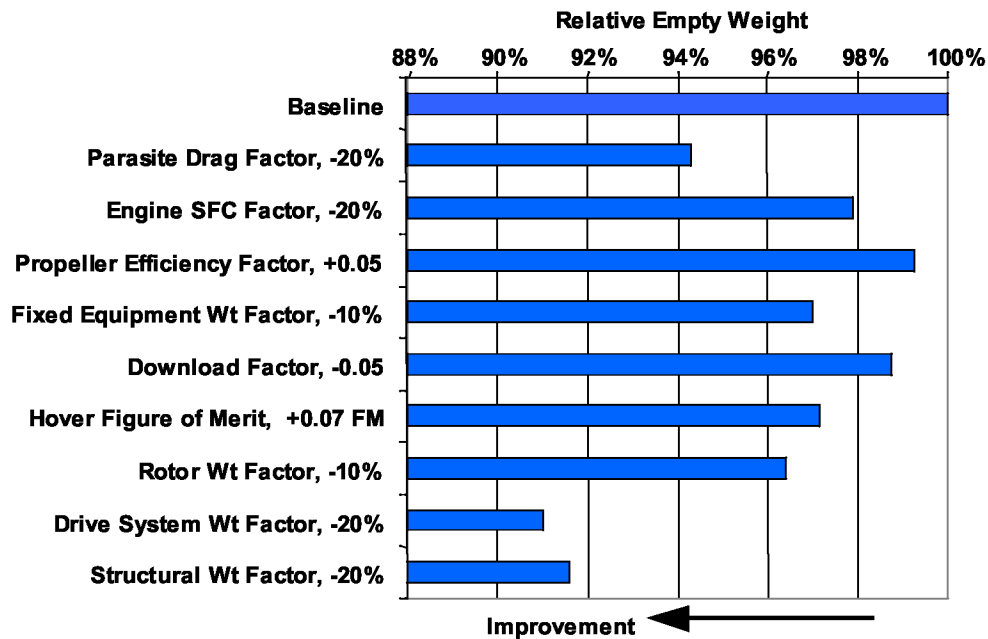
The SMRC helicopter concept used propellers for cruise propulsive force. Although current advanced propellers, such as the 8-bladed NP2000, are breaking new ground in propeller design, discussions with Hamilton-Sundstrand indicated that today's propeller performance is near the limit of what can be achieved at SMRC cruise airspeeds (250 ktas). So advanced propeller design was dropped from further consideration in this study.

Sensitivity of the SMRC DOC/ASM to the assumed technical improvements is shown in Figure 40. Engine SFC provided the most benefit, followed by structural weight, parasite drag, hover Figure of Merit and hover download. Less benefit was derived from the assumed reductions in rotor weight, drive system weight and fixed equipment weight.



**Figure 40. Effect of Technical Improvements on SMRC DOC/ASM**

The SMRC empty weight responded more to the direct effects of reduced structural and drive system weights, and had less response to performance parameters like engine SFC and parasite drag, as shown in Figure 41.



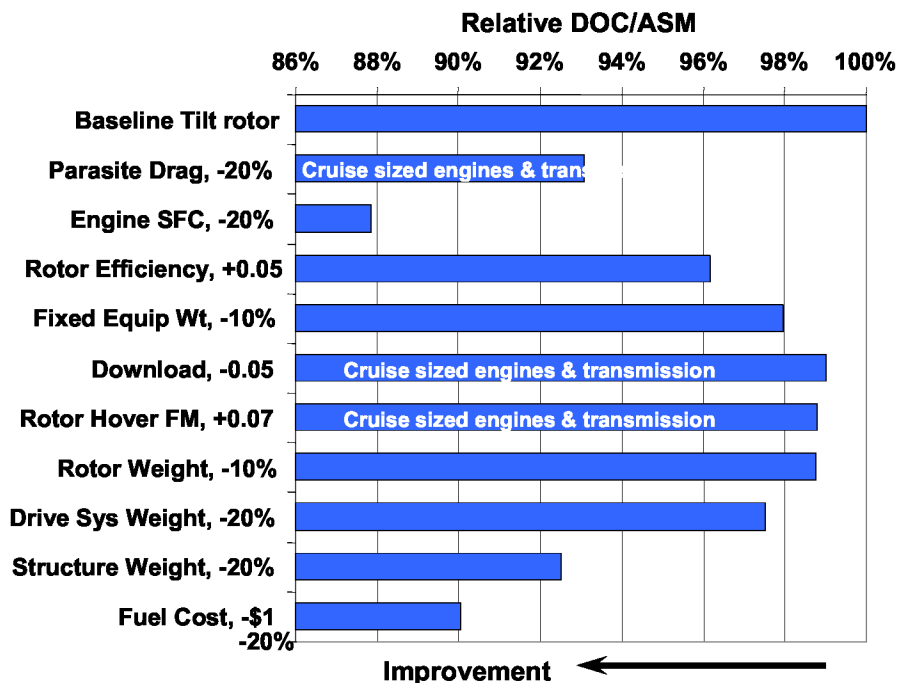
**Figure 41. Effect of Technical Improvements on SMRC Empty Weight**

## 7.2. Civil Tilt Rotor Sensitivity

CTR sensitivity to the same perturbations defined in Table 14 are shown in Figure 42. Results showed reduced engine SFC and a 20% reduction in the cost of fuel were far more beneficial to DOC/ASM than the other technology improvements. The next most beneficial technologies were reduced structural weight

and reduced parasite drag, similar to the SMRC results. However, the CTR showed more sensitivity to overall cruise efficiency than the SMRC. The SMRC showed less than a 4% reduction in DOC/ASM for the 20% reduction in parasite drag, where the CTR showed nearly a 7% reduction in DOC/ASM.

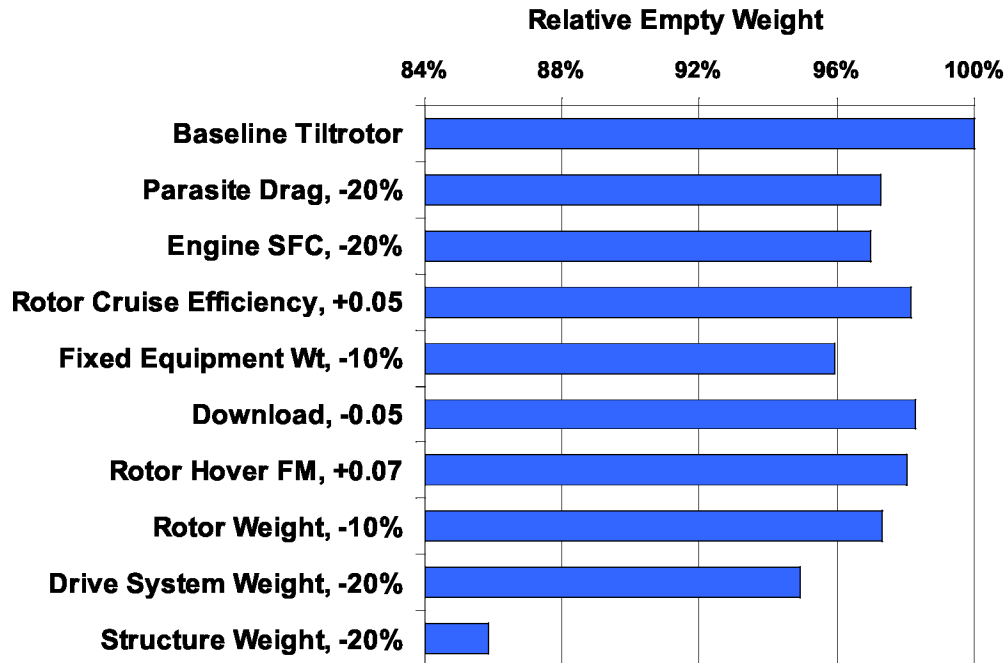
Likewise the CTR showed nearly a 4% reduction in DOC/ASM for increased rotor cruise efficiency, whereas the SMRC showed less than 2% improvement. Consistent with those results, the CTR was less sensitive than the SMRC to improvements in hover figure of merit and download reduction. This fundamental difference in sensitivity can be attributed to the fact that SMRC engine and drive system were sized by hover, whereas the CTR engine and drive system were sized by cruise. Also, the CTR 600 nm range required a higher fuel fraction (10.9% GW) than the SMRC (9.3% GW), making it more sensitive to cruise efficiency than the 350 nm range of the SMRC.



**Figure 42. Effect of Technical Improvements on CTR DOC/ASM**

Sensitivity charts were generated for many parameters, such as the Development Cost, Production Cost and aircraft empty weight. As may be expected, those factors that were most beneficial to DOC/ASM, such as engine SFC, cost of fuel and parasite drag (primarily cruise efficiency) had less effect on aircraft empty weight. Figure 43 shows the CTR empty weight sensitivity to technical improvements. Empty weight was most sensitive to direct reductions of component weights. In order of importance, they were structural weight, fixed equipment weight, drive system weight, and rotor weight. To put this in perspective, one need only look at the fractions of these weight groups relative to the baseline empty weight to understand their order of importance, e.g. 30%, 21.3%, 13.6%, and 14.1% respectively.

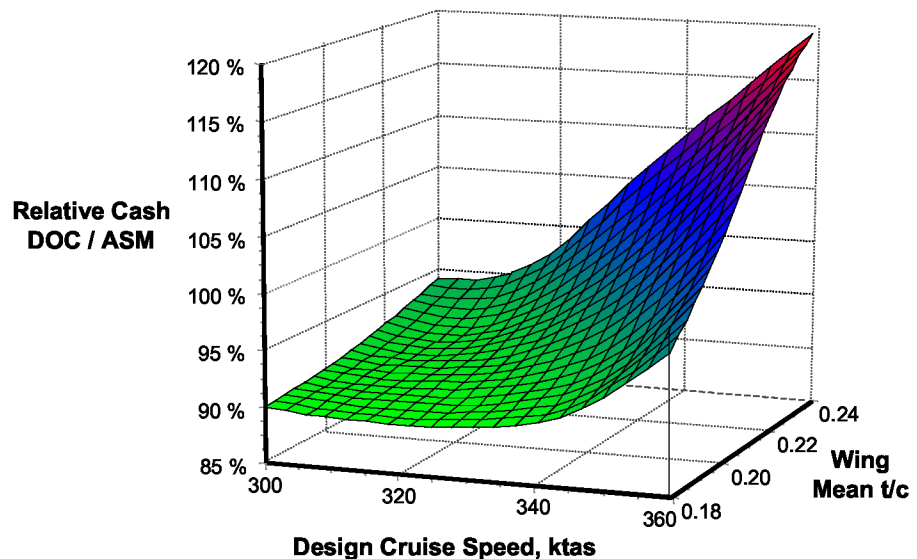




**Figure 43. Effect of Technical Improvements on CTR Empty Weight**

The sensitivities shown above were evaluated independently of each other, each perturbed from the baseline CTR design. However, many of them have interactions with each other and with the operating conditions. The wing thickness ratio affects wing weight, parasite drag and compressible drag, all of which affect cruise performance and therefore affect DOC/ASM. This results in a very nonlinear sensitivity, as shown in Figure 44.

**Figure 44.  
Nonlinear  
Sensitivity of  
DOC/ASM to  
Wing Thickness  
Ratio and Cruise  
Airspeed**



DOC/ASM was relatively insensitive to wing t/c at the 300 knot design cruise speed, but became highly sensitive for design cruise speeds over 320 knots. Similarly, DOC/ASM grew rapidly for the thick wing sections (0.22 to 0.24) as cruise speed increased, but was less sensitive for thinner wings (below 0.20).

The sensitivity of relative development cost and relative production costs were similar to that of empty weight. In general the production cost was more sensitive than the development cost, especially to structural weight and drive system weight. Bear in mind that each bar is for a resized aircraft, so the full impact of the growth factor is reflected in all costs shown in Figure 45.

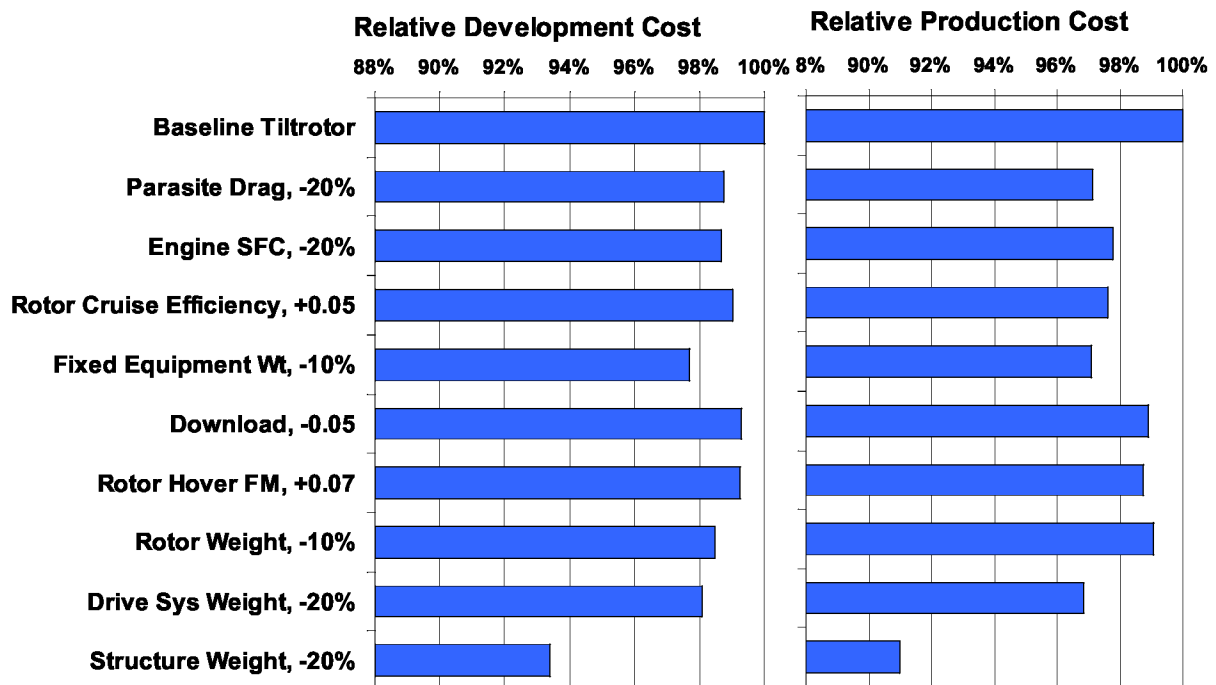


Figure 45. Sensivity of CTR Development and Production Cost to Technical Improvements

### 7.3. Additional Technical Areas

There are several important technical areas that are not readily quantified by a conceptual sizing code because they were beyond the analyses applied in this conceptual sizing. The following five areas were not evaluated by the sensitivity analysis, but they are very significant and technologies that contribute to these goals are addressed separately in this study.

Technical Area	Need
Acoustic Signature	<b>Essential</b> for commercial operations in and around existing commercial airports.
Flight Controls (e.g. HACT)	<b>Highly desirable</b> for Safety, loads, pilot workload
Health monitoring systems	<b>Essential</b> for low maintenance & high availability
Vibration Control (cabin comfort and vibratory loads)	<b>Cabin comfort</b> for passenger acceptance <b>Reduced vibratory loads</b> for lower maintenance
Design for Dynamic Stability (CTR), Blade Flapping Control (SMRC)	Reduced Wing Weight (CTR); Safe Rotor Operation and low gust response (SMRC)

## 8. Candidate Advanced Technologies

Recommendations for advanced technologies were solicited from many constituents, including Chief Engineers and Boeing Technical Fellows who have a broad view of technology within Boeing, and recognized Lead Engineers who are known for their expertise in a particular technical field. Many candidate technologies were identified. Some are in the formative stages of research, with promising performance results at model scale, but lack both full scale tests and valid estimates for the cost of integration and manufacturing. Others are well along the path to maturity, but still require definitive manufacturing processes that validate the technology for the rigors of in-service use before being applied to a production aircraft design.

The technologies were later grouped into sets, ranked, and down-selected as explained in Section 9 of this report. The groups that directly affect aircraft size and performance, and therefore most directly influence costs, were propulsion, structures, drive system, rotor system, fixed equipment, and performance. Several important technical areas do not directly affect aircraft size at the conceptual level of rotorcraft design. Acoustics, health monitoring, and dynamics are addressed in a qualitative nature.

This section presents discussion and descriptions of the candidate technologies, following the priorities established by the previous sensitivity study.

### 8.1. Propulsion Technology

The sensitivity evaluation identified this technology group to be far more beneficial to DOC/ASM than other technology groups, dominated by the possibility of advanced engine technologies producing significant reductions in engine fuel flow. This has a powerful compounding effect. Advanced engines that require less fuel per mile also allow the aircraft to down-size to a smaller and lighter weight, requiring still less fuel for the same configuration.

Many advanced engine programs have been supported by the Army and NASA over the past two decades, from the 3-phased IHPTET<sup>23</sup> program (1987-2005), to the JTAGG<sup>24</sup>, and the current VAATE<sup>25</sup>, AATE<sup>26</sup> and FATE<sup>27</sup> programs. The last three are current programs, emphasizing ‘affordability’ by addressing the critical issues of engine durability, stealth, subsystem integration, health monitoring, thermal management, multi-functional fuel, high energy extraction capability, and emissions. Success is measured via a complex metric.

VAATE is a multi-year, multiple award program with joint participation by the Department of Defense, NASA, and the Department of Energy. Contracts are expected through 2017. It addresses turbo-fan engines for both military and commercial applications with ultimate goals of 200% increase in thrust/weight ratio, 25% reduction in TSFC, and 60% reductions in production cost and maintenance costs.

The AATE and FATE programs are pertinent to civil rotorcraft. AATE is focused on developing turboshaft engines in the 3000 SHP class and FATE is focused on the 7000 SHP class, both to develop the technology and demonstration to TRL 6.

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<sup>23</sup> Improved High Performance Turbine Engine Technology

<sup>24</sup> Joint Technology Advanced Gas Generator

<sup>25</sup> Versatile Affordable Advanced Turbine Engines

<sup>26</sup> Advanced Affordable Turbine Engine

<sup>27</sup> Future Affordable Turbine Engine

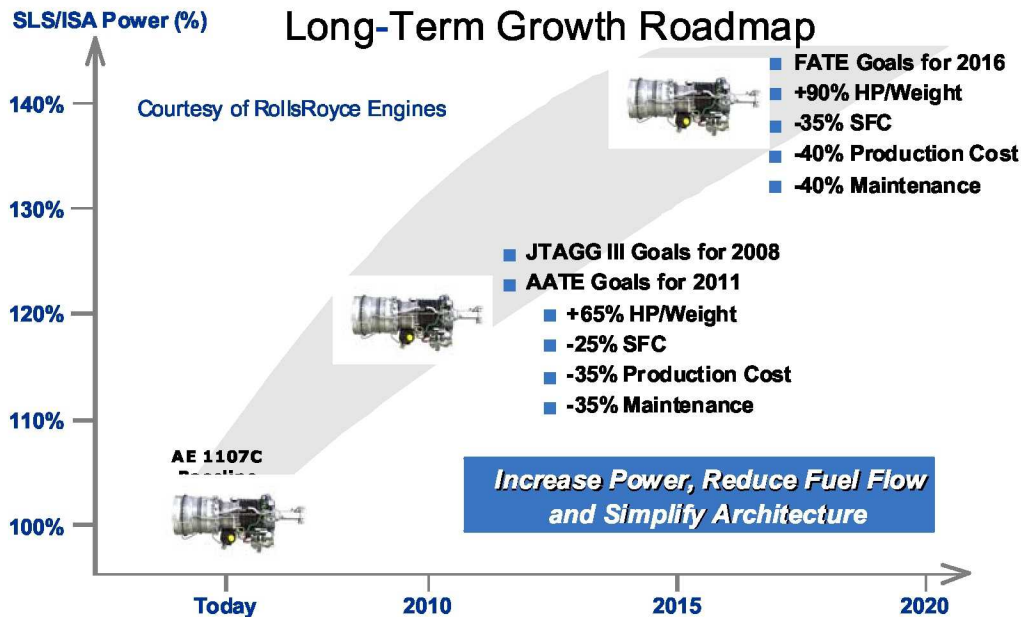
The goals of reduced fuel flow, lighter engines (higher HP/weight), reduced production cost and reduced maintenance are summarized in Table 15. They have been recognized as important factors to reduce aircraft empty weight, gross weight, and operating costs for many years. Success has been achieved and demonstrated to varying degrees in test stand results, but the promise of these goals coming to a production engine has been slow indeed.

Government sponsorship of Research & Development (R&D) programs can develop the technology to make these goals feasible, but it is up to the engine manufacturers and their customers to identify an aircraft product that warrants development and qualification of a full-scale production engine embodying those technologies.

**Table 15. Summary of Advanced Technology Engine Programs**

	Phase		
<b>IHPTET Program (1987-2008)</b>	I	II	III
Specific Fuel Consumption	-20%	-30%	-40%
Power/Weight Ratio	+40%	+80%	+120%
Production Cost	---	-20%	-35%
Maintenance Cost	---	-20%	-35%
<b>JTAGG Program (1997-2008)</b>	I	II	III
Specific Fuel Consumption	-20%	-30%	-40%
Power/Weight Ratio	+40%	+80%	+120%
Production Cost	---	-20%	-35%
Maintenance Cost	---	-20%	-35%
<b>AATE Program (2007-2011)</b>	I	II	
Specific Fuel Consumption	-25%		
Power/Weight Ratio	+65%		
Production Cost	-35%		
Maintenance Cost	-35%		
<b>FATE Program (2007-2017)</b>			
Specific Fuel Consumption	-35%		
Power/Weight Ratio	+90%		
Production Cost	-40%		
Maintenance Cost	-40%		

The graphic in Figure 46 courtesy of Rolls-Royce Engines, displays the goals for advanced engines and the potential for increased power as a consequence of improved HP/weight ratios.



**Figure 46. Advanced Engine Goals Versus Time**

Rotor and propeller design are also elements of propulsion. They are addressed in section 8.6 Performance.

## **8.2. Structures Technology**

### **8.2.1. Introduction**

Structural weight reduction was the second most beneficial category of advanced technologies to enable civil transport rotorcraft. New materials and new manufacturing processes all contribute to a multitude of new, lightweight or less expensive structural options. This section identifies many of the technologies and high-lights a few. These advanced technologies fall into four groups: new materials, advanced analysis methods, new design concepts, and new manufacturing techniques.

#### **New materials:**

- High Modulus Fibers/Prepreg
- Impact resistance honeycomb cores
  - Zylon PBO fiber fabric reinforced Ultracor
  - Bauer PEI tube core
- Thermoplastic resin
- Lightning Strike Appliqué (LSA) for lightning protection
- X-core sandwich panels for weight reduction, and sound absorption.
- Nanotubes for noise and vibration absorption.

#### **Advanced analysis methods:**

- Topology, Topography, Tomometry Optimization
- Post buckled skins
- Global/Local Modeling

**New design concepts:**

- Highly Unitized Structures
  - Intersecting I Grid Stiffened Concept
  - Pultruded Rod Stitched Efficient Unitized Structures Development (PRSEUS)
- Non-orthogonal laminates: higher strength-to-weight

**New manufacturing techniques:**

- High Speed Material Placement/Multi Head Tape Lay-up Machines
- Resin Infusion for low cost structures
- Compression molding
- Continuous Compression Molding (CCM) of Thermoplastics
- Direct Digital Manufacturing (DDM)

Some of these technologies may be familiar, but most have not made their way to production aircraft, or may have crept on as non-flight critical, secondary structure. A major part of the cost of retrofitting new technology into an existing production aircraft is re-qualification, including bench tests, integration tests, and flight test. The expense of retrofitting must be recovered by the cost savings gained from manufacturing many future airframes with the new advanced component..

When advanced structure technologies mature, they can be an integral part of the future design, including manufacture and all qualification.

For example, composite materials make up 25% of the A380's airframe, by weight. Carbon fiber-reinforced plastic, glass fiber-reinforced plastic and quartz fiber-reinforced plastic are used extensively in wings, fuselage sections, tail surfaces, and doors. The A380 is the first production commercial airliner with a central wing box made of carbon fiber reinforced plastic, and it is the first to have a wing cross-section that is smoothly contoured. Other commercial airliners have wings that are partitioned in sections. The flowing, continuous cross-section allows for maximum aerodynamic efficiency. Thermoplastics are used in the leading edges of the slats. The new material GLARE (GLAss-REinforced fiber metal laminate) is used in the upper fuselage and on the stabilizers' leading edges. This aluminum-glass fiber laminate is lighter and has better corrosion and impact resistance than conventional aluminum alloys used in aviation. Unlike earlier composite materials, it can be repaired using conventional aluminum repair techniques. Newer weldable aluminum alloys are also used. This enables the widespread use of laser beam welding manufacturing techniques— eliminating rows of rivets and resulting in a lighter, stronger structure.

**8.2.2. Categorizing advanced structures technologies**

An estimate was made of the potential weight savings of future advanced structures technologies on the primary and secondary structures of civil transport rotorcraft, projecting approximately 20 years into the future. Specifics of the effort described in this section were originally aimed at the Civil Tilt Rotor, although several of the projected savings were also applied to the Single Main Rotor Compound Helicopter.

This was a two step process. The first step identified and categorized advanced structures technologies currently in development that have reasonable expectation of reaching technical maturity and manufacturing readiness levels within 20 years. The second step was to estimate the weight savings of advanced structures technologies for a CTR based on structural components similar to the V-22. The entire aircraft structure was evaluated at the component level based on the VASCOMP group weight statement.

Advanced structures technologies were selected that have a reasonable likelihood of reaching maturity within a 20 year time frame and could be incorporated into a CTR airframe. Most of these technologies are currently under development at various levels of readiness. The advanced structures technologies identified were broken into three categories: materials, manufacturing technology and design.

The weight savings impact of each technology, versus existing industry standard solutions, was estimated and a percentage factor assigned. The technologies with the highest potential for reducing overall airframe weight were then selected for evaluation in the study. The percentage of weight savings in each category are shown in Table 16, Table 17, and Table 18.

**Table 16. Reduced Structure Weight Through Advanced Materials**

<b>Estimated % Weight Savings Relative to Current Technology</b>	<b>Technology Description</b>
50%	Lightning Strike Appliqué' (LSA) – 50% wt saved versus copper mesh, eliminates paint
50%	Integrated antennae and structure – eliminates mounting structure, hardware & cutout, reduces drag (minor weight impact)
25%	Transparent composites – replace window belt with integral skin & windows, windshields
5%	High modulus strain-to-failure fibers & toughened resins
5%	Structural health monitoring <ul style="list-style-type: none"> <li>• Reevaluation of allowables criteria</li> <li>• Embedded sensors to alert BVD occurrences</li> </ul>

**Table 17. Reduced Structure Weight Through Advanced Manufacturing Technology**

<b>Estimated % Weight Savings Relative to Current Technology</b>	<b>Technology Description</b>
5%	Thru-the-thickness reinforcement of skin to structure bond <ul style="list-style-type: none"> <li>▪ z-pinning, stitching (PRSEUS)</li> </ul> Increases toughness & damage tolerance for unitized structures
5%	Advanced manufacturing methods to build more complex structures: <ul style="list-style-type: none"> <li>▪ Allow finer composite tailoring to reduce weight</li> <li>▪ Fiber placement</li> </ul>

**Table 18. Reduced Structure Weight Through Structural Design and Optimization**

<b>Estimated % Weight Savings Relative to Current Technology</b>	<b>Technology Description</b>
30%	Composite rotor drive system components
10%	Aluminum to composite conversion
15%	Structures optimization (apply to frames, beams)
1%	Improved simulation tools – increased confidence in analysis results leads to designing lighter structures
5%	Multi-disciplined Optimization (MDO) <ul style="list-style-type: none"><li>• response of aircraft depends on designed stiffness</li><li>• optimized load alleviation through control surface management to reduce loads on wing/structure</li><li>• could lead to lighter structures</li></ul>

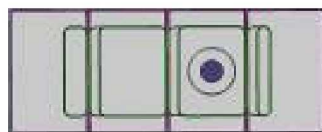
### **8.2.3. Descriptions of advanced structures technologies**

#### **Structural optimization**

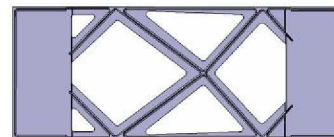
Structural optimization methods currently being developed at Boeing provide convincing evidence to re-think the way aircraft structure is designed. Structural analysis typically involves adjusting many inputs (thickness, area) while monitoring several outputs (stress, stability) to ensure adequate product safety. Simultaneously, the structure must be efficient, economical, and manufacturable.

Structural optimization is a powerful tool that provides many benefits when applied to structural analysis, and is a drastic improvement over the conventional trial and error analysis process. A finite element analysis approach has been developed, documented and substantiated through static and fatigue testing. This approach identifies and adjusts the important inputs and outputs with the goal of achieving a weight optimal structure.

The benefits of using structural optimization are numerous, including load path visualization, weight savings, increased systems design space, improved ballistic protection and fatigue resistance. These benefits offer a compelling incentive to employ this technology into the current design process to improve the performance of engineering products. Trade studies have demonstrated that a 15% weight reduction is feasible for under floor structure on a CH-47 helicopter airframe. Figure 47 contrasts a solid web frame with that of an optimized structure.



**Example Baseline Structure,**



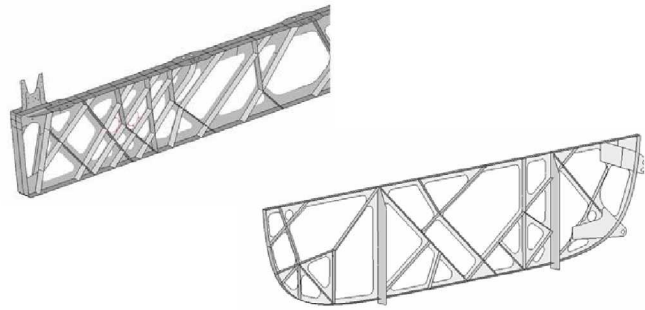
**Optimized Structure**

**Figure 47. Example of Optimized Structure**



### Topology Optimization<sup>28</sup>

This process is used to re-design metallic machined parts such as under floor beams. The process typically offers 15% to 20% weight reductions while remaining cost neutral. Topology optimization is also being explored with composite materials. Examples of frame sections designed and manufactured are shown in Figure 48.



**Figure 48. Frame Sections Designed with Topology Optimization**

### Composite rotor drive components

The Enhanced Rotor Drive System (ERDS) program, funded by AATD and managed by Boeing Rotorcraft, is currently developing critical performance enhancing drive system technologies that have significant advantages over metallic components. The program is designing and testing hybrid composite transmission housings and covers, and braided shafting net-shape molded using Resin Transfer Molding (RTM), see Figure 49. The benefits are reduced part count, enhanced ballistic tolerance (drive shafts), and are estimated to provide up to 30% weight reduction on the part.



**CH-47 Composite Upper  
Forward Transmission  
Cover**

**Figure 49. Composite Upper Transmission Cover**

In addition, the program is integrating embedded sensors within the composite materials to provide the ability to automatically detect critical mechanical component failures.

### Metallic to composite structures conversion

Replacing or converting traditional metallic structures to composite can provide 10% weight savings. Composite materials are inherently stiffer (higher modulus) than metals. In addition, toughened resins are becoming available that provide superior fatigue crack resistance and enhanced performance over metals. Such programs have already been proven in R&D programs, such as implementing braiding technology to fabricate symmetrical parts back-to-back, reducing manufacturing cost and weight.

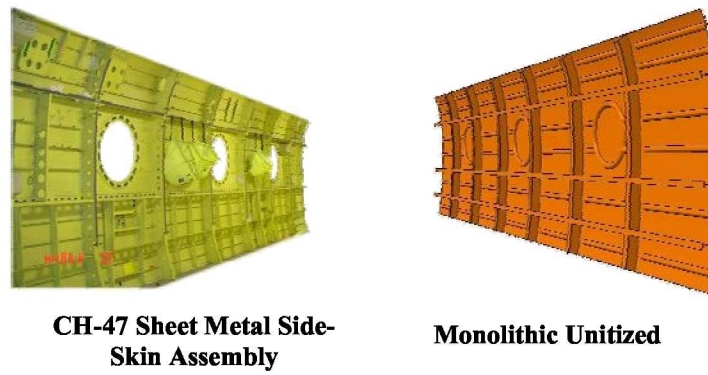
### Advanced manufacturing methods to fabricate increasingly complex structures

The unitization of many parts into a composite monolithic structure has proven to be an effective way to reduce production costs and weight, while increasing the efficiency of the structure. With fewer

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<sup>28</sup> LeRoy Fitzwater, et al; “Topology Optimization Risk Reduction”, Presented at the American Helicopter Society 64<sup>th</sup> Annual Forum, Montreal, Canada, April 29 – May 1, 2008. Copyright © 2008 by the American Helicopter Society International, Inc.

detail parts to manufacture, a drastic reduction in assembly time, fastener count, and number of assembly fixtures can be realized. By eliminating fasteners the structure can be more efficient, since knockdowns associated with stress concentrations around fastener holes are no longer present. Unitization provides a typical 5-10% weight savings over individually hand lay-up and fastened composite components. A comparison of conventional sheet metal construction and a monolithic unitized construction is shown in Figure 50.



**Figure 50. Monolithic Unitized Structure**

Research and development efforts at Boeing have been investigating tooling and manufacturing solutions to enable application of large scale unitization in production processes, such as automated advanced fiber placement lay-up techniques and robotic lay-up. Advanced net-shaped, liquid molding processes are being developed to simultaneously infuse and cure dry fibers, prepreg and pre-cured details allowing more flexibility in the design and manufacture.

The advantages of unitization described above are widely understood and continue to provide incentive for even higher levels of unitization, such as the need to develop new methods for thru-the-thickness reinforcement of skin to structure bonds to increase toughness and damage tolerance (e.g.: Z-pinning, stitching).

### **Resin Infusion**

Approaches for secondary structures incorporate low cost resin infusion technologies such as Vacuum Assisted Resin Transfer Molding (VARTM) and Controlled Atmosphere Pressure Resin Infusion (CAPRI). These technologies can be used to inexpensively fabricate highly unitized, lightly loaded structures. Boeing, Philadelphia, has developed and demonstrated a design and fabrication method for the forward pylon on the H-47 which would be easily transferable to civil rotorcraft. This concept exploits resin infusion's ability to produce complex parts at a low cost. In this case, features such as stiffeners, seal lands, handholds and equipment mounts can be co-cured into detailed parts dramatically reducing cost by eliminating most of the downstream assembly. An example component is shown in Figure 51.

**Figure 51. Re-Designed H-47 Forward Fairing**



### **Advanced Materials, Health Monitoring and Evaluation of Allowables**

With the continual evolution of high modulus strain-to-failure fibers and toughened resins, it can be expected that materials with superior properties will be available within 20 years. Hence, the design of lighter weight structures with equivalent performance can be assumed.

The advent of structural health monitoring (SHM) systems could lead to significantly lighter airframe structures. A SHM system has embedded sensors within the composite materials that continually sweep the structure to monitor for barely-visible-damage (BVD) occurrences, such as internal cracks or delaminations. The sensors provide continuous feedback to a control system regarding the structural integrity of the composite structure. If the system senses damage it sends a signal to a control system where a human response can take place. A structural health monitoring system greatly reduces response time to damage, resulting in increased vehicle survivability.

SHM systems could pave the way to reevaluate materials allowables criteria. This would permit airframe designers to develop advanced structures with slightly reduced safety factors that are lighter and more unitized with no reduction in strength.

### **Transparent composites**

Transparent, load-bearing composite structures are being developed. These materials work by matching the refraction index of the resin with those of the glass fibers, making them transparent across the visible light spectrum with little distortion. The materials also provide advantageous physical properties, shear strength, damage tolerance and impact & abrasion resistance.

When these materials are integrated into the structural design of a civil rotorcraft there are obvious benefits. Transparent composites provide the potential to integrate the numerous cabin windows in a civil rotorcraft with the fuselage skins, eliminating the weight and structural complexity of the window belt. Stronger, lighter windshields of larger size could be designed and manufactured. It is estimated that this technology will lead to a 25% weight savings versus conventional window & windshields.



## Lightning Strike Material Development

Current developments foresee an improved lightning strike protection system for protecting composite structures within an aircraft airframe. These advanced coating materials are called lightning strike appliqués (LSA).

The LSA in development materials are polymer-based, peel-and-stick appliqués which are completely repairable. The benefits are up a 50% weight savings vs. copper mesh as LSA takes the place of both lightning strike copper mesh and paint.



**Figure 52. Lightning Strike Appliqués**

## 8.3. Drive System Technology

As with engine technology, several government-industry programs have focused on development of advanced drive systems and components. A summary of the Department of Defense Rotary Wing Vehicle (RWV) Technology Development Approach (TDA) goals are shown in Table 19.

**Table 19. Government-Industry Drive System Goals**

**Phase 1 Goals: Advanced Rotorcraft Transmissions II Yr 95-00**

- 25% Increase in shaft horsepower / weight
- Double the MTBR
- 10% Support Cost Reductions
- 10 dB Noise Reductions

**Phase 2 Goals: Rotorcraft Drive System-21 Yr 00-05**

- 33% Power Increase
- 25% Production Costs Reductions
- 25% Support Cost Reductions
- 15 dB Noise Reductions

**Phase 3 Goals: Enhanced Rotorcraft Drive System Yr 05-10**

- 40% Increase in Power density
- 30% Production Costs Reductions
- 30% Support Cost Reductions
- 15 dB Noise Reductions
- 75% Automatic Detection of Critical Component Failures

**Phase 4 Goals: Enhanced Rotorcraft Drive System Yr 10-15**

- 50% Increase in Power density
- 35% Production Costs Reductions
- 35% Support Cost Reductions
- 18 dB Noise Reductions
- 95% Detection of Incipient Component Failures

A comprehensive list of drive system technologies was assembled for the civil transport rotorcraft study. The list presented below addresses both the SMRC and the CTR vehicle concepts.

- Multi-speed or variable speed transmissions
  - 2 Speed Transmission
  - Continuously Variable Speed Drives - (mechanical or friction speed control devices)
  - Split torque variable speed face gear main rotor transmission in fuselage, for combining engine power from two nacelles at the main rotor.
- Shallow Angle Face Gear Double Helical Planetary
- Split-torque (face gear) transmission
- Double Helical Planetary System
- Counter Rotating Planetary
- Advanced Planetary gears transmission
- Toroidal Speed Reducers
- Pericyclic Speed Reducers
- Tail Rotor Enhanced power density
- Electrical drive transmission
- Gear material forming processes to yield higher allowables
- Advanced composite materials and methods
  - Advanced composites materials development
  - Metal matrix materials
  - Composite cross-shaft segments with integral couplings.
  - Composite main rotor transmission housings/covers and nacelle transmission housings or covers.
- Split torque face gear nacelle transmission for combining power from two engines in each nacelle to drive a propeller and a wing cross-shaft feeding main rotor transmission.
- Lightweight investment cast housings/covers for smaller gearboxes (has size limit).
- Rotor Drive Shaft material strength improvements (fatigue life improvement in single piece, case hardenable shaft having high core strength).
- Hybrid bearing technology utilizing ceramic elements in all ball and roller bearings.
- Advanced gear and bearing steels.
- Advanced gear processes: laser peening, isotropic super-finishing, near-net forging.
- High contact ratio spiral bevel gears.
- Reduced volume / high convection cooling system.
- Lube sensor development and miniaturization.
- Expanded sensor-based strategy system (ESBS) enabling condition based maintenance (CBM).
- MSPU / VMEP Integration technologies for failure detection and CBM.
- Advanced torque sensor monitoring for multi-rotor torque distribution management.
- Advanced protective coatings for housing corrosion.

All of these technologies are valid candidates, but it is prudent to focus on a few technologies that are expected to provide the greatest ROI for the concepts being evaluated. That presents an issue, given the maturity level of the vehicle concepts that are being evaluated. Considering the major items in the list, it is not easy to decide which technologies are most applicable to the notional drive systems. That is because many of the technologies are dependent upon the vehicle configuration, constraints and requirements

which are largely undefined. For the smaller technology items, such as material improvements, most are applicable to the concept drive systems.

### **8.3.1. Categories of Drive System Technologies**

For this study, a condensed list was developed by grouping the most pertinent technologies in the following way –

- Vehicle dependent drive system configuration technologies;
- System level configuration technologies;
- Component Technologies;
- Material Technologies;
- Tool infrastructure or support system technologies.

There are of course other categories that may also be attractive, such as manufacturing technologies to drive down cost, or Sensors for improved safety, reliability, and reduced operating cost, but this study focused on a high level. A projection of weight reduction (or increase), and other parameters was made for each category based on previous experience or analysis, with a recommendation for technologies that are most beneficial in that category. Projections were made with reference to current legacy fleet experience, and projections are for technology gains expected approximately in the 2020 timeframe. TRL levels cited refer to current state of development.

#### **Vehicle Dependent Drive System Configuration Technologies**

Tilt rotor and compound helicopter systems vehicle dependent technologies primarily focus on 2-speed or variable speed technologies which promote better propulsion system efficiencies but would actually add weight and acquisition cost for the additional functionality. The 2-speed transmissions are practical and near term, whereas variable speed pericyclic (maybe face gear) or toroidal are lower TRL (3 or 4) and would require investment. Currently, Penn State University is working with the Pericyclic concept and Manfred Kuehnle of Toroidal Power Systems is developing the Toroidal concept. These transmission concepts offer an alternative for high reduction final drive systems as well as for variable speed drive systems, though details and actual hardware are in a developmental stage. Weight impacts for these systems are outside our experience base, but estimates from the proponents of those systems range from 15 to 50% (subsystem comparison) weight reduction when configured as final drive units. Projections for this category were taken from the A160 experience, where a 2-speed main rotor gearbox was developed by Boeing Rotorcraft for the turboshaft variant of that aircraft. The 2-Speed Gearbox is applicable to both the CTR and SMRC concepts. An 8% increase in overall drive system weight and 10% additional acquisition cost are estimated for multi speed systems.

Friction drives and electric drive technology do not fit in near term programs. Compound helicopter systems would need drive systems for auxiliary propulsion, so technologies that enable that system integration are applicable. An integration project would potentially save 5% on the overall system weight for the SMRC concept. The tail rotor system power density topics are vehicle specific but don't apply because neither configuration benefits. The following list emphasizes the most relevant technologies where the 2-speed shiftable transmission is the lowest risk and potentially greatest ROI among the group. The other concepts would be viable if they could provide the same benefits. As a group, these technologies would be worth pursuing if they offered an efficiency or operational cost advantage for the aircraft, which can only be determined by Operational Analysis.

- 2-speed planetary shift-able transmissions (TRL6)
- Variable Speed Transmissions - Epicyclic, Pericyclic, Pericyclic with Face gears, Toroidal, Friction based variable speed mechanisms (all are higher risk) (TRL4)
- Split torque variable speed face gear main rotor transmission in fuselage (SMRC specific) (TRL4)
- Integrated and efficient rotor system and propeller drive propulsion systems (SMRC specific) (TRL4)

### **System Level, Configuration Dependent Technologies**

Technologies in this category would be chosen based on the system requirements and constraints. There may be no clear advantage for an individual technology until a detailed design study determines the most beneficial arrangement. Technologies could be ranked as equivalents until studies are completed. The combination of technologies below should yield 20% weight savings for the CTR rotor transmissions, and 10-12% weight reduction for the overall CTR drive system.

- Double helical planetary as output stage (can be combined with other types) (TRL5)  
or Advanced Shallow angle Face Gear Double Helical Planetary (TRL4)
- Split torque nacelle combining transmission (similar to Comanche) (TRL6)

A similar proportion of weight savings would be likely for SMRC concepts with the following technology items. Split torque designs for CTR and SMRC would be most applicable to configurations with 2 engines located at each nacelle. Cost reductions are null but overall noise reductions of 5-10 dB can be expected.

- Split torque face gear nacelle combining transmission
- High Reduction ratio Spiral Bevel Gears (TRL5)

### **Component & Subsystem Technologies**

This group of technologies are applicable to both concepts. They buy their way onto an aircraft in terms of weight reduction or cost benefits and all are applicable to the proposed concepts. An additional 5% overall system weight reduction can be expected through use of these technologies, and noise reductions of 5 dB for the spiral bevel gears, but with a 5% increase in developmental and acquisition cost out of this technology group. The first four technology items are perceived as offering the greatest potential improvement.

- Hybrid Ceramic Bearings (TRL6)
- Advanced Technology Bearings (Wave, Foil, Magnetic) (TRL4)
- Reduced volume / high convection cooling system. (TRL5)
- Efficiency improvements/ Reduced Windage Losses (TRL5)
- Lube sensor development and miniaturization. (TRL7)
- High contact ratio spiral bevel gears (Low Noise) (TRL6)
- Lubricating oil improvements (TRL5)

### **Advanced Material and Processing Technologies**

Material technologies are used wherever possible. Expect another 5% overall system weight reduction through use of these technologies, but with another 5% increase in developmental and acquisition cost for both concepts. The first three technology items are perceived to offer the greatest potential improvement.

- Light metals (titanium) planetary carrier, flanges, and accessory gear and spline applications (TRL6)
- Advanced gear and bearing steels. (TRL4)
- Advanced gear processes: laser peening, isotropic super-finishing, near-net forging. (TRL5)
- Lightweight investment cast housings/covers for smaller gearboxes (has size limit). (TRL6)
- Rotor Drive Shaft material strength improvements (fatigue life improvement in single piece, case harden-able shaft having high core strength). (TRL6)

In this category, composite applications to the heaviest components can yield high weight reductions, but require significant non-recurring engineering effort initially. These technologies offer an additional 8% overall system weight reduction, with a 10% increase in nonrecurring developmental cost and a 5% reduction to support costs due to reduced corrosion and coupling replacement costs.

- Composite cross-shaft segments with integral couplings. (TRL5)
- Composite main rotor transmission housings/covers and nacelle transmission housings/covers. (TRL5)
- Composite Rotor Shafts (TRL4)

### **Tool Infrastructure Or Support System Technologies**

This group of technologies are expected to add another 10% increase in developmental and acquisition cost, but Support Cost may drop by 20% through longer component lives based on direct load measurement and CBM. Noise reductions of 5 dB are expected for the Vibration Reduction technologies. There is also a potential weight reduction with a sensor based torque management system, which will be different between the CTR and SMRC configurations. The projected weight savings for a sensor based torque management system would be 3-5% average but this only offsets weight gains from other items in this category such as vibration reduction actuators or components. The first three technology items are expected to offer the greatest potential improvement.

- Vibration Reduction technologies (TRL5)
- Expanded sensor-based strategy system (ESBS) enabling condition based maintenance (CBM). (TRL5)
- Advanced torque sensor monitoring and torque management (TRL5)
- MSPU / VMEP Integration technologies for failure detection and CBM.

Table 20 summarizes the potential benefits of the above drive system technologies.



**Table 20. Advanced Drive System Technologies**

Drive System Technology		TRL	Component Weight Benefit	Overall Drive System Weight	Development Cost	Production Cost	Support Cost	Acoustics
<b>Vehicle Dependant Drive System Configuration Technologies, note 4</b>							note 5	
2-speed Planetary Shift-able Transmissions	6							
Variable Speed Transmissions	4	+8%	+8%	+10%	+10%	+5%	-5, -10 dB	
Split Torque Variable Speed Transmissions	4							
Total Potential Drive System Benefit			-30.0%	notes +35%	2 +15%	1 -30%	3 -15 dB	
<b>System Level - Configuration Dependent Technologies</b>								
Double Helical planetary output stage, or	6	-12.0%	88.0%	+5%	-5%	0.0%	-5, -10 dB	
Advanced Shallow angle Face Gear Double Helical	4							
Split Torque nacelle combining transmission	6							
<b>Advanced Component &amp; Subsystem Technologies</b>								
Hybrid Ceramic Bearings	6	-4.0%	84.0%	+5%	+5%	0.0%	-5 dB	
Advanced Tech Bearings (wave, foil, magnetic)	4							
Reduced Volume / High Convection cooling	5							
Efficiency, reduced Windage Losses	5							
<b>Advanced Materials &amp; Processing Technologies</b>								
Light metal planetary carrier and accessory gear/spline	6	-6.0%	78.0%	+5%	+5%	-5.0%	0.0%	
Advanced Steels for Gear and bearings	4							
Advanced gear processes (laser peening, isotropic super-finishing)	5							
Lightweight investment cast housings/covers for smaller gearboxes	6							
Rotor Drive Shaft material strength improvements.	6							
Further Investment development:								
Composite cross-shaft segments with integral couplings.	5	-8.0%	70.0%	+10%	0.0%	-5.0%	0.0%	
Composite main rotor transmission housings/covers and nacelle transmission.	5							
Composite Rotor Shafts	4							
<b>Tool Infrastructure and Support System Technologies note 6</b>								
Vibration Reduction technologies	5	0.0%	70.0%	+10%	+10%	-20%	-5, -10 dB	
Expanded sensor-based strategy system (ESBS) enabling condition based maintenance (CBM).	5							
Advanced torque sensor monitoring and torque management	5							

**Notes**

- 1) Support Costs outweigh Development and acquisition costs by a large magnitude for fielded aircraft
- 2) Acquisition Costs may be offset with additional investment in Manufacturing Technology investment
- 3) Noise Reductions are not additive since they can occur at specific frequency ranges
- 4) Not applicable to all vehicles and configurations, performance benefits determined by range and mission requirements
- 5) Noise benefits from rotor quieting at reduced rotor speeds
- 6) Weight reduction of torque management system offset by additional structure and equipment for active vibration reduction system

## 8.4. Fixed Equipment Technology

The category of Fixed Equipment includes a multitude of aircraft systems, including Avionics, Electrical, Hydraulics and Pneumatics, Environmental Control System (ECS), Auxiliary Power Unit (APU), Ice Protection, Furnishings and Equipment (chairs, carpet, wall coverings, galley, lavatory, etc), and cargo handling (baggage handling for the civil aircraft). This extensive group typically makes up 20% to 25% of the aircraft empty weight. It was 21% of the baseline CTR empty weight (Table 12), equivalent to the combined weight of the engine, engine installation, fuel system and drive system. So fixed equipment is clearly important, but does not usually get much attention until Preliminary Design.

One reason is that it is almost entirely purchased equipment, specified by the airframe manufacturer, but with detail design and production subcontracted to specialty companies. One exception is the distribution system for hydraulic lines and electrical wiring. These systems are integral to the airframe, passing through frames and requiring connections and attachments that must be designed around the

details of the airframe. So wiring and hydraulics distribution are often designed and installed by the airframe manufacturer.

A consequence is that historical data for fixed equipment has not been developed into trends for use in Conceptual Design, and advanced technologies in these areas are held by the sub-contractors for competitive reasons. Some technical advances are listed below.

#### **8.4.1. Electrical and Hydraulic**

Application of a high-pressure integrated Electric generator/motor and hydraulic pump (5000 psi) would reduce weight, but the effect on integration and production cost are not well known. Other weight savings would come from fewer power take off pads from the accessory gearbox, consolidating components, and possible elimination of small electric motor driven hydraulic pumps for system check out. Hydro-Mechanical actuators can reduce the complexity of distributed hydraulic lines for multiple hydraulic systems, and have the potential for reducing manufacturing costs. These are already part of the A-380 design and are expected to become prevalent in future aircraft. Once the packaging and cooling issues are solved, the weight savings of electro-mechanical actuator systems will become viable.

#### **8.4.2. Environmental Control System**

Advanced turbo machinery component materials and advanced ducting materials offer some weight savings in future aircraft environmental control systems. Electric driven vapor-cycle systems are expected to be in widespread use for future aircraft due to the lower impact on aircraft empty weight.

#### **8.4.3. Avionics –Open Architecture**

Future avionics suits will be developed with standardized computer platforms. The development of standardized computer modules allows a more efficient use of the software and its resources which is reflected in weight reductions, lower energy consumption, and reduced cooling requirements. Advanced computer modules' form factors will incorporate increased computing density along with advanced flow-through convection cooling techniques. That will allow future computing systems to occupy a fraction of today's computing volume envelope, producing a significantly more compact avionics suit with corresponding weight savings. Advanced materials also allow for more efficient cooling and additional weight reduction.

#### **8.4.4. Furnishings**

Use of advanced materials and analysis methods in the design of seat frames, baggage racks, and galley structure can save substantial weight. Advanced seat designs have smaller form factors and more efficient use of materials.

### **8.5. Rotor System Technology**

Unlike airframe structures that are designed to minimal weight based on loads and structural optimization, rotor blades have to accommodate many conflicting design requirements, often driving the weight higher than expected based on minimum structural margin of safety and fatigue life alone. Blade weight is the result of an alliance between the aerodynamic performance requirements, dynamic frequency placement, stability, structural margin, damage tolerance and high reliability.

Root ends and other joints tend to be sized by strength requirements, while airfoil sections are often sized by dynamic requirements. New technology advancements in the areas of materials, ballistic armor,

health and usage monitoring, and damage tolerance methodology for safety and reliability, have great potential to save weight in rotor blades. While the goal is to save weight, the largest challenge will be to maintain the existing standards on safety and reliability. Some of the key design requirements are reviewed below, highlighting some of the limitations to weight savings, followed by a “best guess” at where technology will be 15 years from now.

### **8.5.1. Rotor Blade Requirements**

Rotor blade definition begins with a near-optimized aerodynamic surface, often with a tapered tip, swept-anhedral tips, or other exotic shape like the BERP tip. Nonlinear twist is commonly used to optimize tilt rotor performance. These features optimize the blade surface for hover and cruise efficiency.

The next goal for the blade design is to derive the lightest possible structure to meet the rest of the requirements. Blade natural frequencies must be placed such that resonance does not occur at the operating frequencies of the rotor. Much of the blade design time is spent tailoring the frequency placement to avoid high fatigue loads and unacceptable aircraft vibration levels, often achieved by moving weight, or adding and subtracting weight at various spanwise locations along the blade. Another alternative is to increase or decrease stiffness by adding or subtracting structural weight. The airfoil regions of rotor blade designs of recent past have not been sized by structural loads, but by dynamic frequency placement, making weight optimization difficult.

In the case of the A160 blade, frequencies are placed so high that there are no issues operating the blade at several different RPM's. While this approach requires extremely stiff and light materials, some damage tolerance and ballistic tolerance is compromised due to the use of brittle, high modulus carbon fiber.

Traditional carbon systems have brittle failure modes compared with fiberglass. Damage propagates quickly in carbon and large stress concentrations can lead to rapid structural breakdown. The M55J employed in the A160 design is twice as stiff as IM7, but has a lower strain to failure and poor damage tolerance. Present day limitations on extremely stiff carbon fibers requires research for better compressive allowable and increased damage tolerance. Optimized material systems could exist in 15 – 20 years that may enable the use of high modulus carbon.

Bond lines (at extremely cold temperatures) and fiber composite structures are often compromised at hot-wet temperatures. The spar wall must have enough thickness to prevent moisture from saturating a thin spar wall. One solution to this issue would be the invention of a surface coating that would be impervious to moisture intrusion. If moisture could be reduced or eliminated, strength reductions due to high temperatures are not as significant. Such a coating does not exist today.

From a durability perspective, rotor blades have to operate in very harsh environments. Sand and rain wreak havoc on the useful life of a composite rotor blade. Extremely hot or cold environments can compromise the strength of composite systems. A blade designed to absolute minimal structural margins of safety often runs the risk of being retired early. The use of improved damage tolerance materials, advances in new erosion systems, and material coatings to eliminate moisture intrusion could dramatically improve the durability of rotor blades.

Summarizing, weight savings can come from many sources. Some of the more likely are listed below.

- Materials and coatings that both inhibit erosion and moisture intrusion.
- Lighter, stiffer materials like high modulus carbon fibers may be combined with optimized material systems, addressing some of the downside to high modulus carbon, by the 2020 time frame.

- Damage tolerance applied early in the design phase could realize some weight savings. Structures could be engineered to breakdown gradually, a precondition for an on-condition approach to part retirement.
- Health and usage monitoring with onboard diagnostic systems could monitor loads and flight events to determine when it's time to retire parts. If combined with load control, a good deal of weight can be saved in the rotor blade as well as the rest of the vehicle.

New material systems and less conservative methods of providing safety and reliability offer the potential to reduce rotor blade weight (and hub weight as that tends to reflect the blade weight). It is not unreasonable to assume that blade weight can be reduced by 20% by 2023, and meet all design requirements for safe and reliable operations.

### **8.5.2. Advanced Materials Technology for Rotor Hubs**

#### **Nanotechnology**

Current research has shown it is possible to double the tensile strength (145 ksi) of aluminum by using nanotechnology, which is probably at the low end of its potential. This technology can be used to improve metal fatigue characteristics as well as strength. In a 15 to 20 year time frame, a helicopter hub part using this technology could possibly be reduced in weight by 20% - 40% compared to a conventional steel or aluminum component. Nanotechnology is especially useful in the development of hard coatings.

#### **Metal Matrix Composites**

This term usually refers to materials that are made from powdered metals and are blended and formed into rough shapes (much like a forging) that can be machined into finished parts. This technology has the potential for a 15% to 30% weight saving in hub components at reasonable cost and improved damage tolerance. This technology is probably more developed than nanotechnology for aluminum and is already being considered for aircraft components.

#### **Ceramics**

Modern ceramic technology has the potential to replace steel materials in rolling element bearings, with improved tolerance to loss of lubrication compared to steel due to its high temperature tolerance. The estimated benefit is a bearing weight reduction of 5% to 15% over conventional bearings.

#### **Carbon Fiber Composites**

Homogeneous materials like metals are the favored material for rotor hubs because of the many precision details on rotor hub components required in a small space (lugs, bores, threads). However, in limited applications a 15% to 30% weight saving from carbon fiber composite technology may be feasible if a part assembly can be replaced with carbon fiber.

#### **Fluid-Elastic Damper Technology**

Fluid elastics used in dampers refers to a damper that is a combination of rubber (usually natural rubber) and damping fluid (probably silicon based). The advantage of a fluid-elastic system would be reduced maintenance cost.

### **8.5.3. Advanced Rotor Hub Concepts**

Bearing-less designs or a minimal number of bearings in a hub are the concepts to explore to achieve weight and maintenance improvements. While elastomers are heavier and more costly, one main spherical

elastomeric bearing (and possibly a smaller stabilizing bearing) per blade arm is all that is needed in a coincident hinge concept. This single main bearing approach is not any heavier or costlier to produce than a multi-hinge blade arm and could reduce weight by 10% to 15% and reduce maintenance cost as well. Development cost for hubs with a minimal number of bearings would be comparable to multi-hinge hubs.

The ideal situation, of course, is the use of carbon fiber and fiberglass technology to eliminate all bearings in a bearing-less rotor head concept. Development costs would most assuredly be high, but this type of rotor hub may offer weight saving of 15% to 30%. These weight savings are not necessarily in addition to the material weight savings mentioned earlier because the new designs would probably depend on some of those materials mentioned.

## **8.6. Technologies for Rotor Performance**

Options for advanced rotor systems that are applicable to the CTR or the SMRC include the following:

- The Reconfigurable Rotor Blade (RRB)
- The Smart Materials Activated Rotor Technology (SMART)
- An Advanced Rotor Design for Tilt Rotors
- An Advanced Rotor Design for Compound Helicopters

### **8.6.1. Reconfigurable Rotor Blade**

The RRB program was funded by an ONR S&T effort to demonstrate the ability to morph a rotor blade twist schedule in flight to improve aircraft performance. The project began in 2002<sup>29</sup> and concluded with a ¼-scale wind tunnel test in 2007. The test successfully demonstrated the ability to twist the blades in flight, measure performance changes, and control the system for simultaneous motion.<sup>30, 31</sup> Performance improvements were uncertain due to improper built-in twist in the model blades, but the actuation system worked well, proving the potential.

The RRB system is shown in Figure 53. The core is a NiTiNol alloy based actuator. NiTiNol is a Nickel-Titanium alloy originally developed by the Naval Ordnance Laboratory. The alloy can be “trained” to have a different shape depending on temperature. The material will transition between austenite and martensite grain structures at approximately 160-180°F. The actuator is mounted in the blade root and is connected to an outboard bulkhead via a composite torque tube. Heating or cooling the NiTiNol will induce a blade twist change. The actuator to torque tube interface is made through an over-center mechanism that holds the blade in either hover or cruise mode twist until the system is commanded to move. No external power is required while the system is in either stable position. An integrated thermal management system allows the actuator to function in temperatures ranging from -30 to +140°F.

The program focused on performance benefits for tiltrotor aircraft and used the V-22 Osprey as an initial technology transition opportunity. The system was conceived as a retrofit to existing aircraft; constraining the design in terms of overall blade geometry, weight, stiffness and dynamic properties.

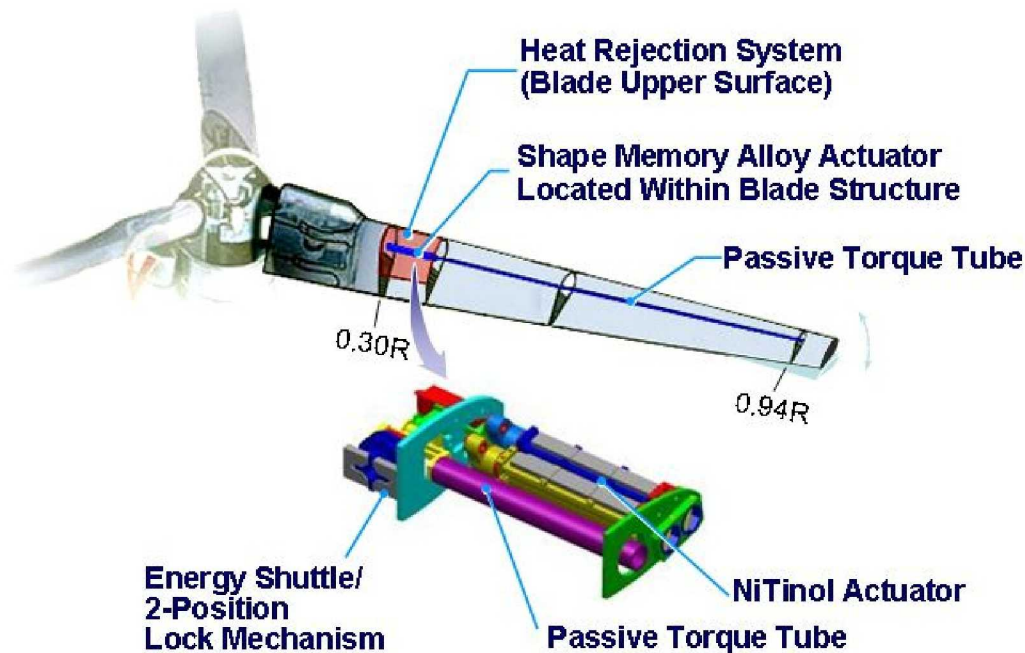
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<sup>29</sup> R. Ruggeri, D. Jacot, and D. Clingman, “Shape memory actuator systems and the use of thermoelectric modules”, SPIE Smart Structures and Materials Conference, April 2002, San Diego CA.

<sup>30</sup> Arbogast D. J., Ruggeri R. T., and Bussom R. C., “Shape Memory Actuator Design for the Reconfigurable Rotor Blade”, Smart Structures and Materials, SPIE 6930-21, March 2008.

<sup>31</sup> R.T. Ruggeri, D.J. Arbogast, and R.C. Bussom “Wind Tunnel Testing of a Lightweight ¼-Scale Actuator Utilizing Shape Memory Alloy”, 16th AIAA/ASME/AHS Adaptive Structures Conference, April 2008

Analysis for the V-22 indicated that payload gains of approximately 2000 pounds are achievable while maintaining or increasing cruise performance.



**Figure 53. Reconfigurable Rotor Blade Concept**

### **8.6.2. Smart Materials Activated Rotor Technology**

Vibration noise, and rotor aerodynamic design compromises continue as barriers to further improvements in flight performance and mission effectiveness of rotorcraft. The Smart Materials Activated Rotor Technology (SMART) rotor blade has trailing edge flaps actuated by on-blade smart material actuators. This concept emerged as a primary candidate to dynamically alter (i.e., morph) the blade structure and aerodynamics, and thus apply limited authority active control to achieve significant improvements in rotorcraft performance and mission capability. Full scale wind tunnel tests demonstrated that this advanced technology can provide:

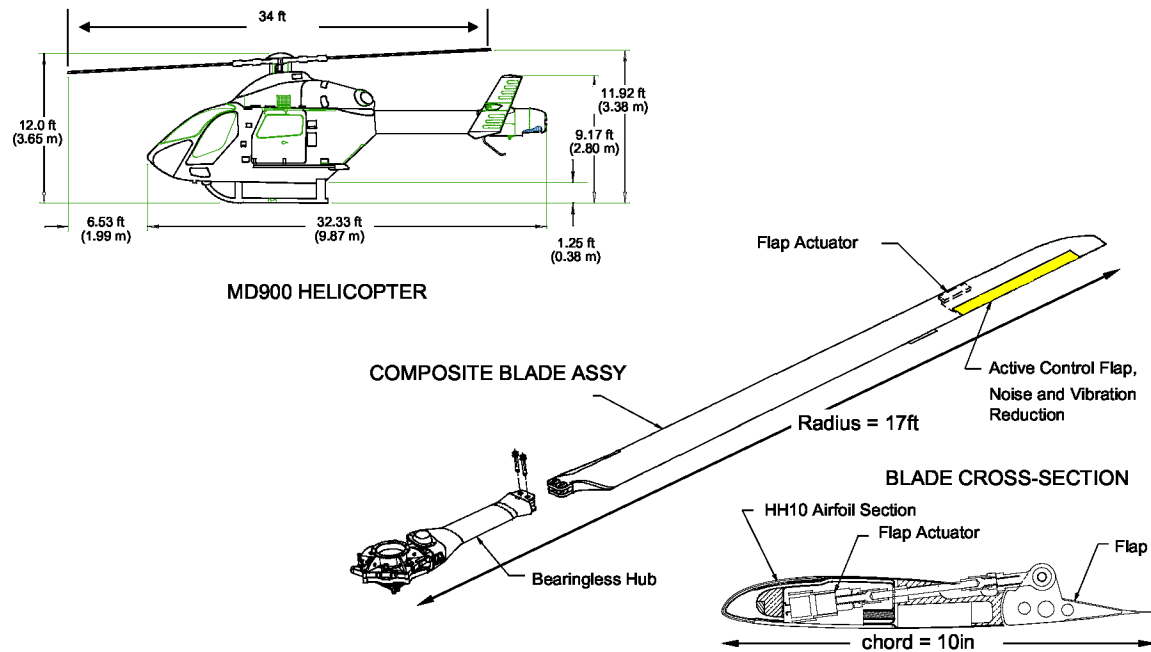
- 80% vibration reduction,
- 8 dB BVI noise reduction for a helicopter passing overhead, and
- 6 dB reduction in high-speed impulsive (in-plane) noise.

Simulation indicates the possibility of 6%-10% improvements in rotor L/D in high speed flight.

Resulting benefits are alleviation of vibration in cruise flight, reduced acoustic footprint, improved performance, and significantly improved life cycle cost, availability and fleet readiness. An Air Force study estimated that vibration reductions of this magnitude could reduce failure rate and corrective maintenance by 40%, yield corresponding life-cycle cost reductions of 10%, and at the same time increase fleet readiness.

Boeing has developed the technology and demonstrated that smart material actuated flaps are feasible and practical for high bandwidth, limited authority active control of a helicopter main rotor. The MD900 Explorer twin engine, light utility helicopter was selected as the demonstration vehicle. Its state-of-the-art five-bladed composite, bearingless main rotor system was modified to include on-blade piezoelectric

actuators and trailing edge flaps, Figure 54. Whirl tower testing of the SMART rotor was conducted in 2003 with full rotor instrumentation and a five-component balance. The rotor was tested for 13 hours under a range of conditions, including seven hours of flap operation. Flap inputs included open loop static and dynamic commands. The flaps showed excellent authority with oscillatory thrust greater than 10% of the steady baseline thrust (6,000 lbs). The whirl tower test demonstrated the feasibility of the concept.



**Figure 54. MD900 and SMART Rotor Blade with Active Control Flap**

Forward flight testing of the SMART rotor was conducted in a 2008 test in the NASA Ames 40' x 80' wind tunnel, Figure 55<sup>32</sup>. The effectiveness of the active flap for noise and vibration control was demonstrated conclusively, with preliminary results showing significant reductions in BVI and inplane noise as well as vibratory hub loads. The impact of the flap on control power and rotor smoothing was also demonstrated. Data evaluating any benefits in aerodynamic performance and impact on flight controls were also acquired, but will need more detailed evaluation. The flap actuation system proved very reliable, as did the instrumentation and data systems.

The authority, effectiveness, and reliability of the flap actuation system were demonstrated in more than 60 hours of testing at up to 155 knots and 7,700 pounds thrust. The effect of open and closed loop active flap control on rotor loads, noise, and performance was evaluated. Feedback parameters included rotor balance forces and moments as well as microphones. Several closed loop control algorithms were also tested.

<sup>32</sup> Kennedy, D.K., Straub, F.K., "Design, Development, Fabrication and Testing of an Active Flap Rotor System," AHS Annual Forum, Grapevine, Tx, 2005





**Figure 55. SMART Rotor in NASA Ames 40x80 Wind Tunnel**

### **8.6.3. CTR Rotor Design**

#### **Baseline CTR Blade Design**

The baseline rotor for this study of a Civil Tilt Rotor is therefore based on the current and proven design of the V-22. The civil transport rotorcraft spends the great majority of its time and fuel in cruise, and very little time and fuel in hover. Furthermore, takeoff and landings will be from prepared sites, away from terminal areas, passengers, and ground crews. So downwash/outwash in hover are of far less concern than must be applied to rescue helicopters or to military rotorcraft that work and land over unprepared sites with troops or rescue personnel in the rotor wake.

A critical issue for the CTR rotor is noise during approach and in the terminal area, requiring lower rotor tip speeds in hover, while the rotor tip speed in cruise is constrained by Mach number limits of the outboard airfoils at cruise airspeeds from 300-400 ktas.

The baseline rotor blade design should provide this civil application with acceptable cruise performance, applying the V-22 airfoils and planform as current technology, but selecting blade twist and tip speed for good cruise propulsive efficiency at 300 to 350 ktas airspeeds and cruise altitudes of 20,000 to 25,000 ft. Tip speeds were selected to stay within a helical tip Mach number of 0.825, as shown in Figure 56. The V-22 rotor cruise tip speed stays within the self-imposed limit of 0.825 helical Mach number up to 300 ktas at 24,000 ft. But tip speed must be substantially lower to achieve cruise airspeeds of 350 ktas or higher. The rotor advance ratio increases significantly as airspeed increases and tip speed decreases, driving the ideal blade twist to less than the V-22 with unknown impacts on blade loads at lower airspeeds or in the conversion corridor.

The challenge is to pick a hover tip speed and solidity for acceptable low speed performance, and a combination of rotor planform, twist and cruise tip speed that will keep all blade sections operating below the drag divergence Mach number of the local airfoils. The target cruise speed of 350 ktas for the advanced CTR rotor required a 600 fps tip speed and less twist than the V-22.



The CTR baseline rotor was intentionally based on a 300 ktas cruise condition, representing current technology and therefore being similar to the V-22 rotor geometry, except with four blades. Hover tip speed was reduced to 750 fps, significantly less than the current V-22 hover tip speed of 810 fps. Cruise tip speed was 637 fps, operating at 85% of hover RPM (about 30 fps lower than the V-22). Figure 56 indicates this rotor should satisfy the helical tip Mach number goal up to about 320 ktas cruise airspeed at 24,000 ft. A description of the baseline CTR rotor blade is shown in Figure 57.

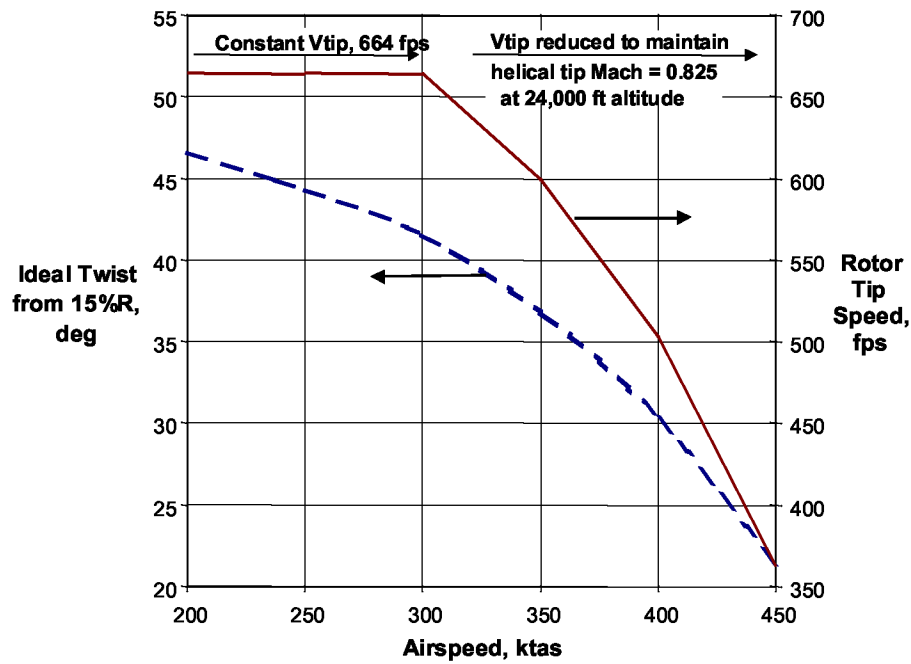


Figure 56. CTR Rotor Cruise Tip Speed and Twist Versus Design Airspeed

#### Baseline CTR Rotor:

- 4 Blades
- Thrust-Weighted Solidity = 0.103
- Twist =  $41^\circ$  from 15%R (300 kts,  $V_{tip}$  = 637 fps)
- No sweep or tip taper
- Airfoils: XN series
  - Root: XN-28, 0.28 t/c
  - Tip: XN-09, 0.09 t/c

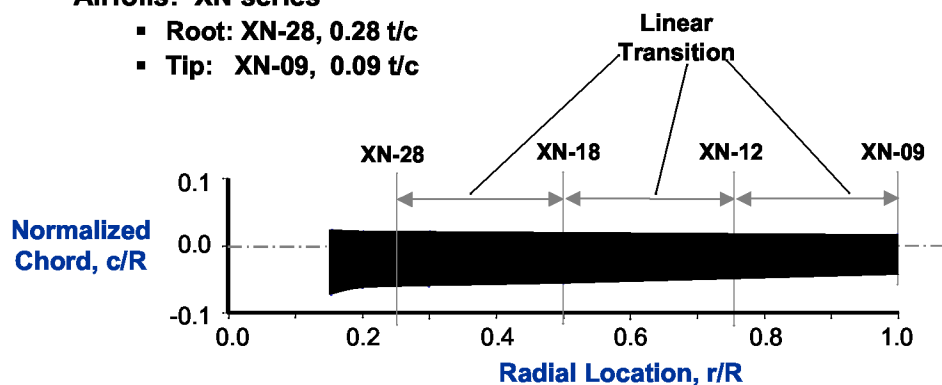


Figure 57. CTR Baseline Blade Design

## Advanced CTR Blade Design

Advanced tilt rotor blade designs for high-speed cruise were explored in detail in the 1993 Boeing study conducted for NASA<sup>33</sup>. That study explored rotor blade airfoils, planform taper and tip sweep to improve cruise propulsive efficiency with a minimum loss in hover performance. Unfortunately, no wind tunnel tests were performed to corroborate the analytical results.

Rotor performance for that study was calculated with the b08 axial flow analysis for both hover and cruise flight at a 400 ktas target airspeed. Some results were repeated with the higher-fidelity TECH-01 code, which confirmed the basic analysis. TECH-01 also identified small but significant differences in cruise performance due to blade elasticity. Cruise tip speeds and blade planform in that study were strongly influenced by the V-22 design. A 600 fps tip speed was selected for the 400 ktas cruise airspeed, yielding a helical tip Mach number of 0.89, which is beyond the airfoil's drag divergence Mach number (MDD) even at zero CL. Tip sweep was used to reduce the chordwise Mach number. Lower cruise tip speeds to further back off from MDD were not evaluated, based on then current knowledge of the V-22 RPM limits. A brief summary of results is provided as relevant technical background to this study.

Several blade planform geometries were examined, using the XN18 airfoil (18%) inboard, with linear variation to the Boeing VR-12 airfoil (10.6%) at 40%R, linear variation to the Boeing VR-15 airfoil (8%) at 80%R, with constant VR-15 from there to the tip. Twist distributions were adjusted for swirl, local inflow, and the zero lift angle of the local airfoil.

The baseline (reference) blade was unswept with no inboard taper, but had parabolic tip taper beginning at 85% R. Operating at 600 fps tip speed, it gave a cruise propulsive efficiency of 0.78 at 400 ktas, 25,000 ft.

The blade design with the best cruise efficiency had 0.67 planform taper to 85%R with parabolic taper from there to the tip and non-linear sweep beginning at 78%R. This blade achieved 0.796 propulsive efficiency at 400 kts.

Generally speaking, blade designs that performed better at the high cruise speed also performed better at lower airspeeds, at least down to 300 ktas which was the lowest speed analyzed.

The study also evaluated inverse linear taper, with a normal taper outboard of 75%R. This design for cruise produced 2% higher propulsive efficiency at the 400 ktas design point, but stalled in hover at a slightly lower  $C_T/\sigma$  and was dropped from further study.

An equivalent rotor design performed today would examine more variability of both planform and operating tip speed.

An advanced blade design was developed for a 350 ktas cruise airspeed. Hover tip speed and solidity were initially selected for acceptable hover and low speed performance. The rotor planform, twist and cruise tip speed were then analyzed and selected to keep all blade sections operating below the drag divergence Mach number of the local airfoils during cruise. The 350 ktas target cruise speed for the advanced CTR rotor required a 600 fps tip speed, and less twist than the V-22.

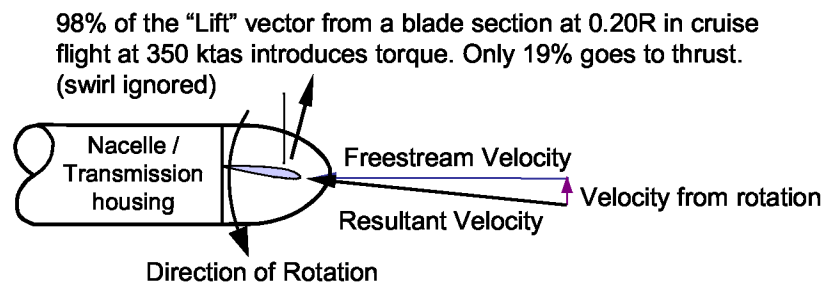
It must be noted that the advanced blade design and considerations which follow were not conducted with a high fidelity CFD analysis, nor was the planform optimized. Cruise tip speed was selected to keep the helical tip Mach number below 0.825 and twist was determined by the advance ratio, as a fallout of

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<sup>33</sup> Dadone, L, Derham, R, Liu, J., Wilkerson, J., Yablonski, M, Ziegenbein, P., "Detailed Rotor Design Trade Study", NASA Contract NAS2-13607, August 1993

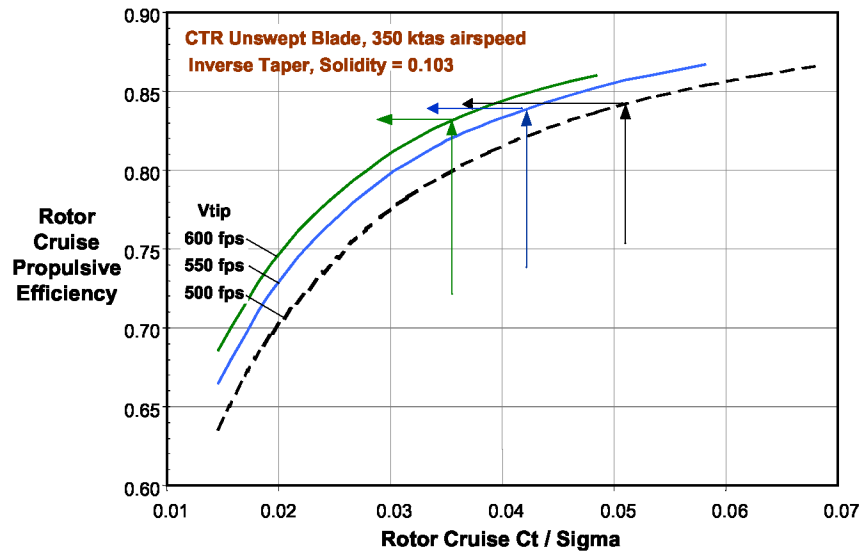
the target cruise speed and the rotor tip speed. So the value of the following charts and this definition of an “Advanced” rotor for CTR is to show that substantial gains in tilt rotor cruise performance are feasible, without significant loss in hover efficiency, by applying basic analysis tools. A more comprehensive design of an advanced high-speed rotor for tilt rotors, applying higher fidelity analysis methods for the aerodynamic performance, definition of blade structural properties, and aeroelastic analysis would be a very worthwhile R&D program for future civil tilt rotors.

Planform is an interesting parameter for a high-speed rotor. Early propellers had essentially no airfoil inboard of about 30% radius, just a substantial shank to carry the loads, and for good reason. During high-speed cruise, the inner most blade sections are subject to the same free-stream dynamic pressure as the rest of the aircraft, so there is potential for substantial “lift”. But the inboard rotational speed is insignificant compared to the free-stream, resulting in a “lift” vector that is in the plane of rotation rather than in a thrusting direction. A velocity diagram looking at an inboard blade section from the side of the propeller shows the ideal blade angle is nearly aligned with the free-stream flow, see Figure 58. So the lift vector of the inner most blade elements produce essentially no propeller thrust. Instead, “lift” from this inboard blade element primarily produces torque that must be overcome with shaft power, rather than useful thrust. Similarly, drag from the inner blade sections is aligned with the freestream, counteracting the useful thrust generated by the outboard, productive blade sections. And this is compounded by the addition of induced drag if the inner most blade sections developed “lift”. A better design may be to reduce this undesirable “lift” from very inboard blade sections, as early propellers did, if that were an acceptable configuration for the hover mode.



**Figure 58. Lift Vector Of An Inboard Blade Element In High-Speed Cruise**

Several cruise tip speeds were initially evaluated, all for a 350 ktas cruise airspeed and with twist distributions appropriate for their advance ratio at that airspeed. Results from an early trade-off (at an initial solidity of 0.103) showed the 600 fps tip speed had higher cruise efficiency at a given cruise  $C_T/\sigma$ , see Figure 59. However, comparing rotor propulsive efficiency at the different tip speeds for the same thrust, marked by the vertical arrows in that figure, show lower tip speeds have a slight advantage with diminished benefit below a tip speed of 550 fps.



**Figure 59. Evaluation of Several Tip Speeds on Rotor Cruise Performance**

It would be worthwhile to follow through on that improvement in a competitive detailed design. But the lower cruise tip speed of 550 fps would require a 73% rpm in cruise relative to the 750 fps hover tip speed, with implications on engine performance and/or the drive system. It was beyond the scope of this study to carry those design details through to a conclusion, so the 600 fps tip speed was deemed acceptable for cruise.

Improved cruise performance at the 350 ktas design condition was the true goal of this exercise and that determined all the blade features except for solidity. The blade planform selected for the advanced CTR blade has a slight inverse taper over the inboard blade to reduce the undesirable inboard forces that contribute so little to propulsive thrust, and places more blade chord in the outboard productive section of the blade. The axial flow analysis used in reference 33 predicted improved cruise performance for this inverse taper, while retaining a good hover figure of merit. But a higher fidelity analysis is really needed to optimize such a geometry; to more accurately predict local inflow velocity, and to account for the aerodynamic interactions between blade sections. This is especially true to develop the tip shape in light of the importance of acoustic goals during approach and landing. Outboard taper was applied to further alleviate the impact of helical Mach numbers on cruise performance.

The selected 600 fps cruise tip speed for the advanced CTR rotor blade gave a respectable rotor cruise propulsive efficiency of 0.83 at an 80% cruise rpm (600 fps/ 750 fps). The helical tip Mach number is 0.82 at the 350 ktas design cruise speed and 24,000 ft altitude/ISA. This design condition corresponds to 0.985 advance ratio, which determined the 36.8° twist, measured from 15% radius to the blade tip.

The advanced blade design for the CTR is shown in Figure 60. The “ideal twist” is simply the local helical inflow angle, normalized to zero at 75% R. If all airfoils were uncambered, this would give a theoretical uniform angle of attack along the blade radius. The ideal twist does not account for the radial variation of airfoil lift at zero angle of attack due to distributed camber, so the inboard cambered airfoils operate at slightly higher lift coefficients. The advanced design blade can be compared to the baseline blade design by comparison to Figure 57.

### Advanced CTR Rotor

- 4 Blades
- Thrust-Weighted Solidity = 0.112
- Twist =  $-36.8^\circ$  from 15%R
- No sweep
- Inverse inboard taper, tip taper
- Airfoils: VR series outboard  
XN series inboard

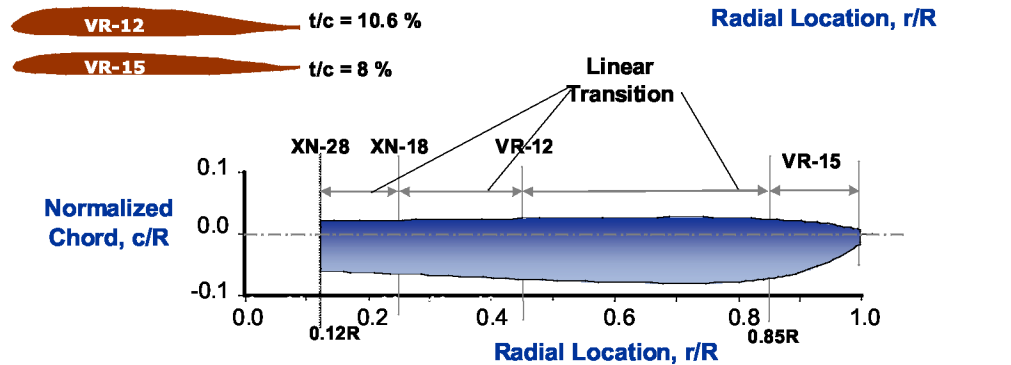


Figure 60. CTR Advanced Blade Design

Although the advanced CTR rotor blade has several degrees less twist than the V-22 blade, it has far more twist than conventional helicopters, and, as may be expected, it performed well in hover. Hover performance for the advanced CTR blade was predicted with the Boeing b08 axial flow program using the airfoil and planform distribution shown at a 750 fps tip speed. Results for hover figure of merit (FM) are shown in Figure 61.

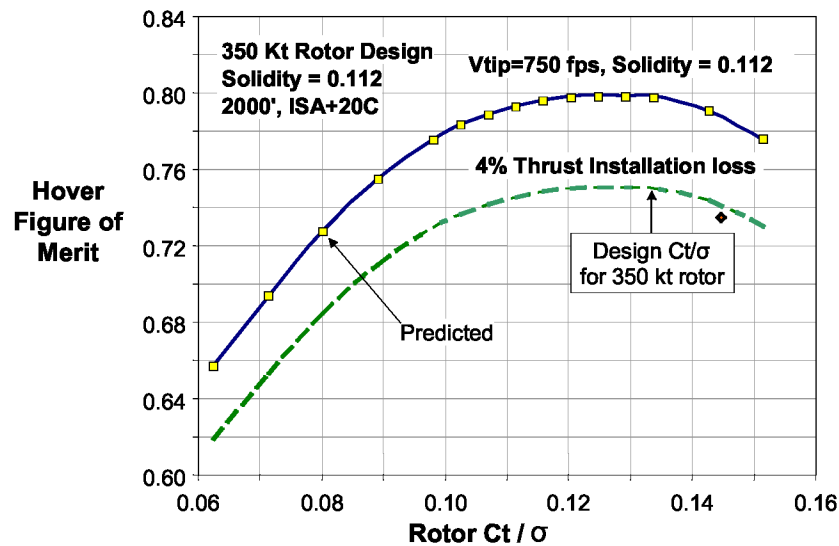


Figure 61. Hover Performance for the Advanced CTR Rotor Design

The isolated rotor achieved a FM of 0.80, indicating the light inverse inboard taper did not hurt hover performance. A knockdown of 4% of thrust for installation losses gave a respectable installed FM of 0.75 (matching the FM of the high-speed rotors from ref 33). Reduced hover tip speed for acoustic relief would of course require an increase in solidity, with consequences to cruise efficiency.

Predicted cruise performance for the CTR baseline and advanced rotor is shown in Figure 62. Both rotors were generating the estimated cruise propulsive force required to overcome drag. Performance of the CTR advanced rotor is a substantial improvement over the baseline rotor at 350 ktas. In fact, the predicted cruise propulsive efficiency of the advanced rotor at 400 ktas is better than the propulsive efficiency of the baseline rotor at 350 ktas.

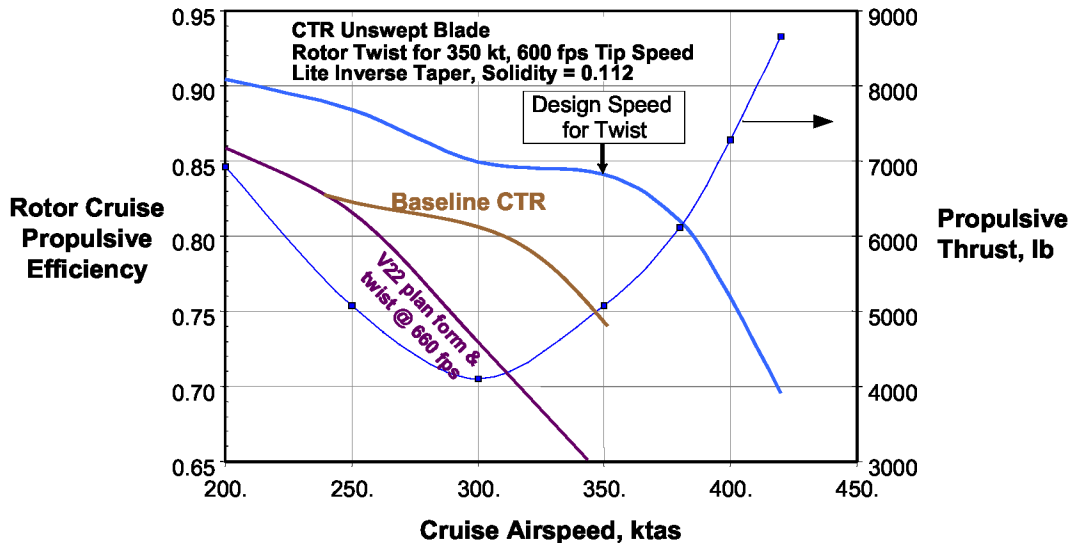


Figure 62. Cruise Performance of the Advanced CTR 350 Knot Rotor Design

A variant of this blade was designed for a 400 ktas cruise speed by reducing the tip speed to 500 fps, adjusting the twist for the new advance ratio of 1.35, and applying tip sweep by shearing the tip airfoils. It gave further performance improvements – a propulsive efficiency of 0.785 at 400 ktas – viable for a 400 ktas cruise condition.

#### 8.6.4. SMRC Rotor Design

##### Baseline SMRC Blade Design

The baseline SMRC main rotor aerodynamic design emphasized the 250 knots cruise airspeed (at 20,000 ft) flight condition, in which the aircraft's propellers offload the rotor propulsive force 100%; the aircraft wing unloads the rotor lift 90%; and the rotor RPM is slowed to 84% of hover RPM to limit the advancing tip Mach number. The baseline rotor design is defined below and shown in Figure 63.

- Disc loading at Design Gross Weight = 15.0 lbs/ft<sup>2</sup>
- Hover tip speed = 650 ft/sec
- Rotor slowed at high airspeeds to limit  $M_{AT}$  to 0.81, resulting in 546 ft/sec at the design cruise condition
- Thrust-weighted solidity = 0.13
- Five blades,
- Twist = -5°, linear
- 30° swept (quarter-chord), tapered tip ( $\lambda = 0.6$ ), beginning at 0.92R
- Airfoils: Boeing VR-12,  $(t/c)_{MAX} = 0.106$  ; Boeing VR-15,  $(t/c)_{MAX} = 0.080$
- Airfoil distribution: VR-12 root to 0.85R, linear transition to VR-15 at 0.92R, VR-15 to tip

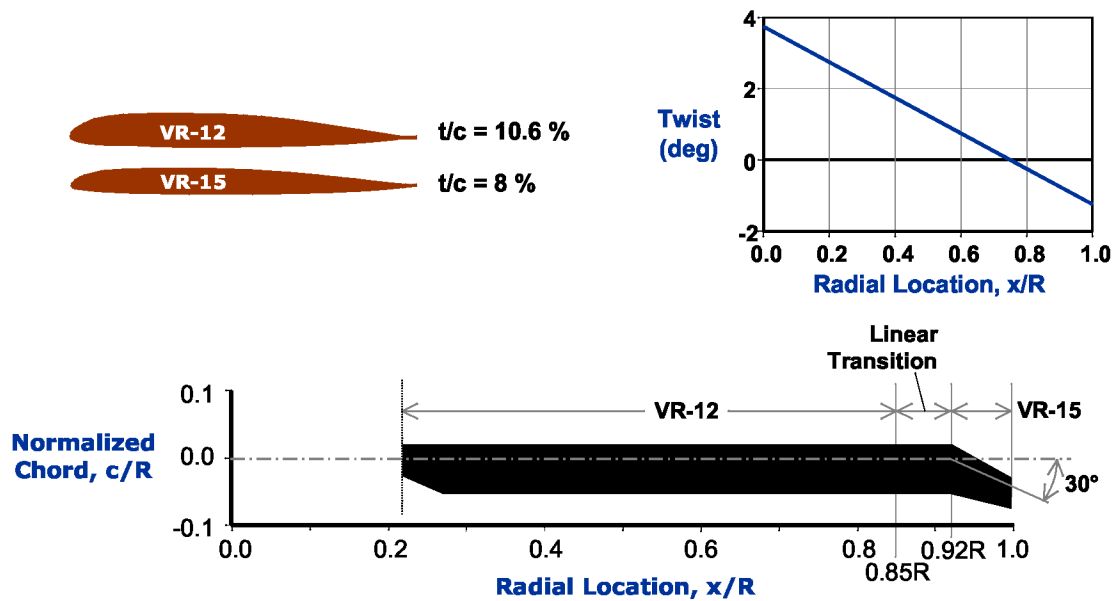


Figure 63. Baseline SMRC Rotor Blade

Rotor hover performance was predicted with the rotor hover analysis code EHPIC. At the design mission takeoff condition and gross weight, the rotor tip Mach number is 0.567, the HOGE  $C_T/\sigma$  is 0.1466, and the predicted rotor Figure of Merit is 0.707, see Figure 21. This relatively modest Figure of Merit reflects the low twist and the high solidity, which were chosen for the baseline design from considerations of reducing vibratory rotor loads at high speeds. Therefore, it is considered likely that improved passive design features can provide significant improvement in hover performance, on the order of five to ten percent (Figure of Merit increase of 0.035 to 0.07).

### Advanced SMRC Blade Design

The advanced SMRC passive blade design was primarily for hover, as the hover condition sized the installed engine power and main rotor transmission rating. The application of SMART rotor technology is expected to be an enabling technology for SMRC, providing control of vibratory loads, enhancing trim capability, and perhaps providing real-time response to alleviate gust loads and rotor loads during normal maneuvers. However, 85% of the cruise power is driven by the propellers, so rotor cruise efficiency has a secondary influence on overall fuel demand.

The proposed advanced technology passive blade design features are:

- Compound tip anhedral (i.e., combined dihedral and anhedral).
- Increased overall twist.
- Nonlinear, tailored twist in the tip region.

The tailored twist is not really an advanced technology, but will increase the need for advanced technologies for rotor vibration reduction at the 250 knots cruise speed. Alternatively, the additional 6° of twist in hover could be achieved with the Reconfigurable Rotor Blade technology of section 8.6.1. That would allow low twist, or no twist, in cruise.

Previous analytic and experimental studies indicate that blade tip anhedral of 20° will provide two counts of Figure of Merit. Increasing overall twist by 6° will provide about two counts improvement in Figure of Merit; and nonlinear, tailored twist will contribute about two counts of Figure of Merit. With



these three passive blade design improvements, predicted rotor Figure of Merit improves by the ratio  $(0.707 + .06)/0.707 = 1.085$ . Thus, it is concluded that at least an 8% improvement in the hover performance of the SMRC Baseline design can be achieved.

The SMRC rotor will require advanced technologies to control blade flapping and reduce vibratory loads at the 250 knots cruise condition.

### SMRC Propellers

Advice from Hamilton-Sundstrand was that current propeller technology achieves near the maximum performance in the 250 ktas speed range of the SMRC, so the same propeller efficiency was used for the advanced SMRC.

However, considerable advances have been made in propeller design over the past 60 years, especially during the past decade. The three propeller configurations in Figure 64 show a trend to more blades and higher solidity for turboprop application. While a comparison of these propellers' performance in cruise and for static thrust would be interesting, it was not considered a new technology that would benefit most rotorcraft, and so it was not pursued.

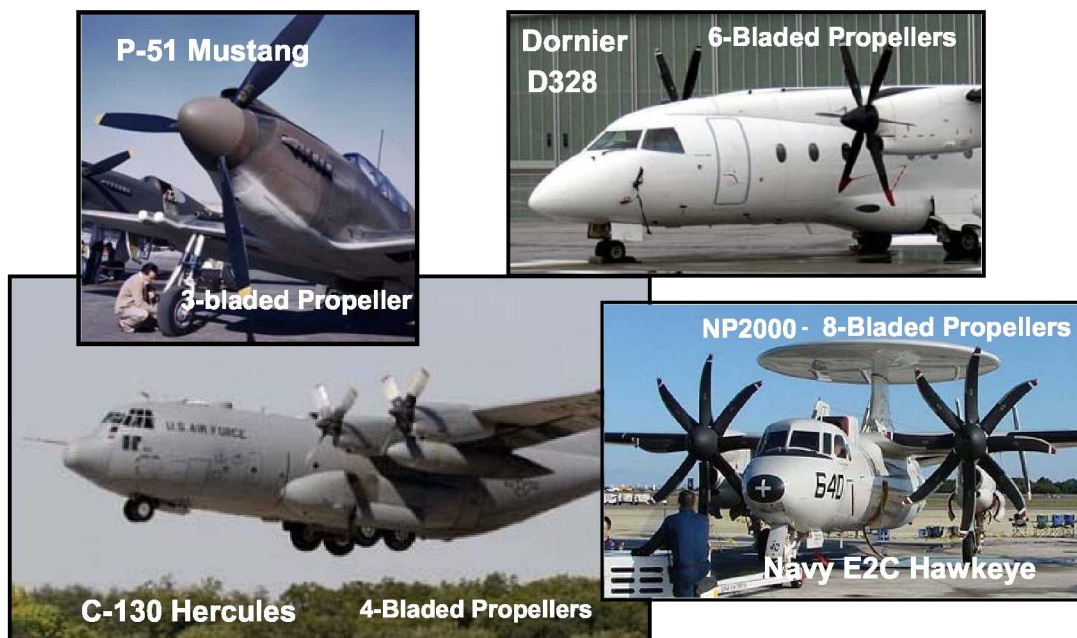


Figure 64. A Comparison of Four Propellers

## 8.7. Technologies for Airframe Performance

### 8.7.1. Active Flow Control

Active Flow Control (AFC) refers to use of small, distributed surface orifices which energize local flow conditions by means of very low, or zero, oscillating mass flow, in order to delay boundary layer separation. As a relatively new technology, AFC has been proven to reduce drag and several possible applications have been explored in model scale wind tunnel tests. A flight demonstration using the XV-15



was successfully conducted in 2003 to show that AFC could reduce download on the wing flaps in hover, improving overall tilt rotor lift capability. AFC has yet to see application in a production aircraft.

There have been three known implementations of AFC.

- Early active control of the boundary layer by *periodic* addition/subtraction of mass flow via surface jets required a source of air with significant mass flow.
- Electro-mechanical zero-net-mass-flow (ZMF) types use an electrically vibrated diaphragm inside a closed cavity connected to the surface slot by a nozzle. State-of-the-art ZMF actuators are small, lightweight, and self-cooling.
- The micro fluidic jet actuator. This new actuator is simple, reliable, has no moving parts, and only requires a supply of compressed air to operate. The actuator is self-cleansing due to a continuous low-level air flow, keeping it free of sand, dust, or water contamination problems. One implementation is manufactured by Advanced Fluidics Corporation<sup>34</sup>.

There are several potential applications for rotorcraft listed below, and discussed briefly in the succeeding paragraphs.

- Profile drag reduction for wings, especially for thick airfoils
- Drag reduction for helicopter pylons and possibly rotor hubs
- Reduced download in hover for tilt rotor configurations
- Increased lift coefficients and expanded stall boundary by delayed separation
- Increased flap effectiveness by delayed separation

### **AFC for Wing Profile Drag**

Dr. Preston Martin, U.S. Army AFDD, stated that test experience with application of AFC to streamlined, two-dimensional, lifting components such as wings indicates that the AFC can limit a typical wing profile drag coefficient (based on planform area) to 0.008 up to a wing lift coefficient of at least 1.0 (and possibly to 1.2).

A 10.5%-scale V-22 semi-span wing and nacelle model was tested with in the 3 ft x 4ft wind tunnel at the University of Arizona. The test showed substantial reduction in the wing drag with installed micro fluidic actuators placed at 30% flap chord. Figure 65 shows a 66% increase in lift-to-drag ratio (L/D) with the micro fluidic actuators over the baseline data without AFC.

The wing span of the SMRC baseline design was determined by the requirement for separation between the rotor and the propellers, so as the design wing area is reduced by the use of AFC on the wing, the expected increase in wing induced drag due to the high lift coefficient is offset by the increase in wing aspect ratio, which reduces induced drag.

Therefore, it seems probable that the SMRC Baseline design would not realize any significant drag reduction due to application of AFC to fuselage areas other than the rotor pylon area.

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<sup>34</sup> Gregory, James W., and Sullivan, John P., Raman, Ganesh., and Raghu, Surya., "Characterization of a Micro Fluidic Oscillator for Flow Control", AIAA 2004-2692, 2<sup>nd</sup> AIAA Flow Control Conference, Portland, OR, June 28 – July 1, 2004.

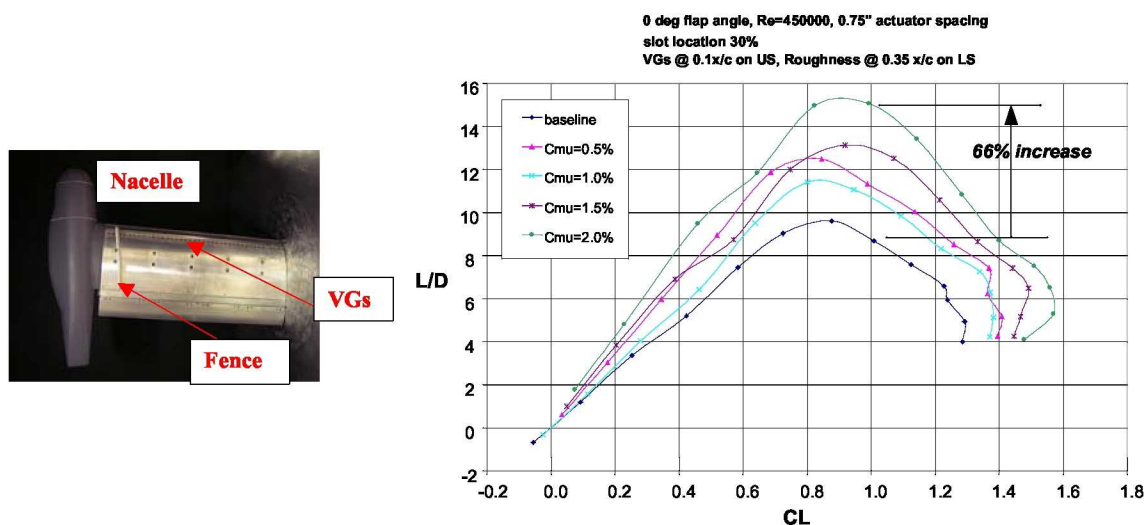


Figure 65. Effect of Active Flow Control on Wing Lift-to-Drag Ratio

### AFC to Reduce Rotor Hub and Pylon Drag

In the SMRC baseline design, the rotor hub and pylon parasite drag and interference drag from that region constitute 50% of the total baseline design drag. Dr. Preston Martin stated that test experience with application of AFC to bluff aircraft components, such as a rotor hub and pylon, indicates that up to 50% drag reduction could be achieved by applying AFC in a very tailored manner to the pylon and the upper fuselage and wing area near the pylon. This would require an analytical and experimental development of the AFC configuration; including a multi-entry, medium-to-large-scale, wind tunnel test series.

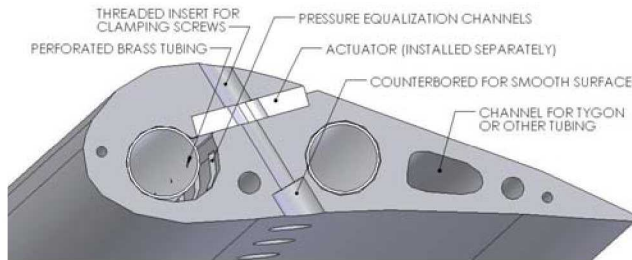
To approach this level of 50% drag reduction on the hub and pylon, it may be necessary to extend the aft portion of the pylon up behind the rotor hub. AFC would be applied to this extended portion of the pylon also, so as to, in effect, “streamline” the hub. Application of AFC to the rotating hub, even if it incorporates a hub fairing, was not expected to be worthwhile.

### AFC for Hover Download Reduction

Control of separation using *periodic* blowing has been demonstrated on airfoils and bodies such as cylinders and aircraft fuselages. A flight demonstration of AFC on the wing flaps of the XV-15 was successfully conducted in 2003 and achieved reduced download.. The technique is to periodically inject and remove air from the surface boundary layer through a slot that is located upstream of the flow separation point.

Scale model tests of AFC for download reduction were conducted on a refurbished and calibrated 10.5% scale powered V-22 hover model rig at the University of Arizona<sup>35</sup>. A view of the wing flap with the embedded AFC device is shown in Figure 66.

<sup>35</sup> Lucas, Taubert, Woszidlo, & Wagnanski of University of Arizona; and A. McVeigh of Boeing; “Discrete Sweeping Jets as Tools for Separation Control”, Paper presented the 4th AIAA Flow Control Conference, June 23-26, 2008, Seattle, WA

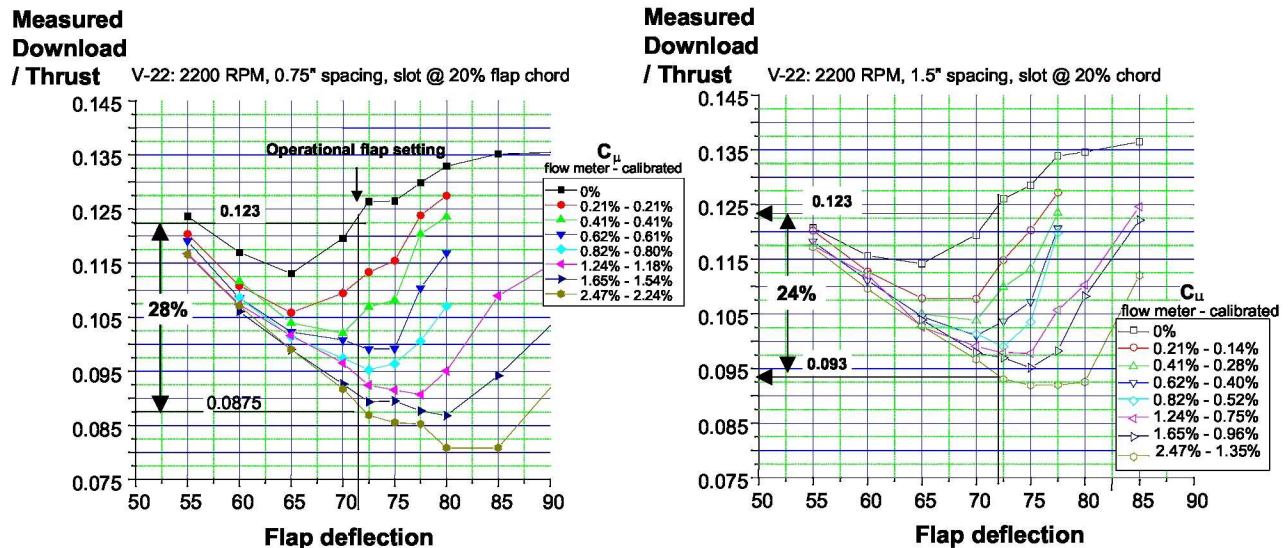


**Figure 66. Cross-section of Wing Flap with AFC**

Spanwise spacing of the actuators was tested at 0.75 inches and at 1.5 inches, installed in both wing flaps at 20% flap chord and subsequently at 30% flap chord. The rotors were run at an rpm and blade collective pitch to give a thrust coefficient ( $C_T$ ) of 0.016, which is representative of V-22 hover. The flap angle was varied and the download measured. Figure 67 shows the variation of download/rotor thrust with flap deflection for various values of momentum blowing coefficient with actuators at the 20% flap chord position, for both spanwise spacings.

This 0.75 inch spacing reduced the download/thrust by 28%, at the V-22 operational flap setting of 72 degrees, corresponding to a 2000 pound increase in hover lift (equivalent to more payload). The 1.5 inch spacing was still very effective, reducing download by 24% for the same conditions, still a very substantial gain.

Although these download tests were made with a scale model, and the data show some scatter, the aerodynamic results are expected to be very similar at full scale because the download is almost totally caused by the pressure drag from the separated flow over the wing with deflected flap. As with any new technology, full scale designs and demonstrations are required to firmly establish the difficulty and cost of integration, such as a source of pressurized air supplied through a distribution system, dependability of the system, and consequences of system degradation or failure on aircraft safety.



**Figure 67. Effect of AFC on Wing Download in Hover**

## Other AFC Applications

Another possible application of AFC is to reduce interference drag at wing/fuselage and wing/nacelle junctions. However, data are not available to estimate the amount of drag reduction that could be expected.

Dr. Martin stated that recent experimental (wind tunnel) efforts to reduce drag on a CH-47 fuselage by means of AFC produced no measurable drag reduction.

### 8.7.2. Parasite Drag Reduction

AFC can reduce wing drag at cruise lift coefficients, significantly improving cruise L/D, as shown in Figure 65.

CFD analysis is not commonly used to reduce parasite drag of helicopters since the airspeeds are generally low, and approximately half of the total vehicle drag comes from separated flow around the hub and pylon region(s) rather than parasite drag. However, parasite drag reduction for either of these high-speed civil transport rotorcraft (SMRC or CTR) is very important. Their civil mission is dominated by long cruise segments rather than hover and low speed flight, such as EMR, border patrol, news or police helicopter missions. So parasite drag is a significant part of overall drag and therefore impacts the cruise horsepower and fuel consumption that drives aircraft size. The relatively high cruise speeds of the SMRC (250 ktas) and the CTR (300-350 ktas) further emphasize the need for reduced parasite drag.

Assume the civil transport cruise is at best range speed, where induced drag equals profile drag, then the total drag is approximately twice the profile drag. For example, parasite drag of the baseline CTR, Table 10, includes skin friction drag, excrescences, interference drag and momentum losses. Basic drag of the wing and fuselage make up about 70% of the total, and these would be the prime candidate areas for parasite drag reduction. A 20% reduction in the parasite drag of the wing and fuselage would yield a 14% reduction in total airframe drag.

$$\left( \frac{\text{New } C_D}{\text{Baseline } C_D} \right) = \left( \frac{\text{New } C_{D_0}}{\text{Baseline } C_{D_0}} \right) = 0.30 + 0.70 * (1 - 0.20) = 0.86$$

Similarly, the operating cruise L/D of the CTR, Figure 36, is about 11.5. The same 20% reduction in parasite drag of the wing and fuselage would increase the cruise L/D to roughly 13.4, as indicated by the equation below.

$$\text{New} \left( \frac{L}{D} \right) \approx \text{Baseline} \left( \frac{L}{D} \right) * \left( \frac{\text{Baseline } C_{D_0}}{\text{New } C_{D_0}} \right) = \text{Baseline} \left( \frac{L}{D} \right) * \left( \frac{1}{0.86} \right)$$

There are several approaches to reduce drag. Some are design choices, and some are the application of high-fidelity analyses that are not commonly applied to rotorcraft design, except for hover conditions.

- Design decisions such as wing thickness ratio that effects wing  $C_{D_0}$  and compressibility drag.
- Manufacturing methods for surface smoothness to delay thickening of the boundary layer and boundary layer separation.
- Advanced airfoil design that could further reduce profile drag and alleviate compressibility.
- Application of CFD to the overall wing-fuselage-empennage design would reduce total drag by optimally reducing interference drag.
- Application of AFC technology could reduce drag in particularly difficult areas, as previously described.

### 8.7.3. Advanced Wing Design

The concept of advanced wing design for rotorcraft is seldom mentioned, but these cruise-defined civil transport rotorcraft may require that for efficient cruise. The distribution of wing chord, airfoil profile, thickness ratio and twist should be determined with the same fidelity as current fixed wing transports to maximize cruise L/D.

It is very unlikely that the wing of a tilt rotor aircraft would have a highly tapered planform like commercial fixed wing transports. Tilt rotor configurations tend to optimize at high wing loadings, in the absence of high lift requirements for takeoff and landing. A highly tapered planform for a CTR has either a very narrow chord at the nacelle, or maintains a suitable chord at the nacelle for structural reasons in combination with a wing extension outboard of the nacelle. For the same wing area, the added area of the extended wing must reduce the wing chord inboard of the nacelle. The best solution for either configuration requires an optimized geometry to obtain the best combination of structural efficiency and high cruise efficiency.

The application of sophisticated analysis tools and model-scale wind tunnel tests could optimize the wing for cruise, reduce interference at the wing-body and wing-nacelle juncture, and address low-speed handling requirements. This would likely increase the aircraft cruise L/D by 10%.

### 8.8. Advanced Flight Control Technology

Any future CTR or SMRC will leverage full authority Fly-By-Wire (FBW) Flight Control System (FCS) technology to maximize vehicle productivity, flight safety, and flight path command precision while minimizing pilot workload. Digital FBW technology enables proven flight control functions such as Structural Load Limiting (SLL) that have reduced requirements for load bearing structural weight by roughly 40% on the V-22 Osprey<sup>36</sup>. FBW technology is also an enabler of advanced rotorcraft configurations such as the SMRC because it eliminates the weight penalties and performance constraints associated with applying mechanical flight control systems to non-traditional control surface effectors and variable geometry air vehicles. The SMRC will apply FBW flight control technology to balance propeller thrust optimally throughout the flight envelope, using differential thrust for anti-torque in hover and equalizing thrust for efficient propulsion in cruise. The SMRC will also control main rotor forces and moments in high-speed cruise through a Digital FBW FCS which will reject gusts and alleviate rotor loads. Regime recognition algorithms implemented in the digital flight control systems of future CTR or SMRC aircraft will adapt control augmentation unobtrusively throughout the flight envelope to optimize ride quality, gust rejection, and dynamic component structural usage characteristics.

The Boeing 787 program took the bold step of instituting a new multidisciplinary design process, referred to as “Lines, Loads, and Laws”, that integrated the aerodynamics, structures, and flight controls functional disciplines to minimize structural weight of the 787 by exploiting Fly-By-Wire (FBW) flight control technology to a far greater extent than previous programs. The “Lines, Loads, and Laws” effort was pivotal in conceptual, preliminary, and detailed design of the 787 and is viewed as one of the critical new technologies that has shaped and enabled the concept of the super-efficient 787 Dreamliner. While static “never-exceed” loads are of paramount importance in fixed wing aircraft design, rotorcraft design is influenced primarily by high cycle fatigue inducing dynamic loads that can often be exceeded for brief

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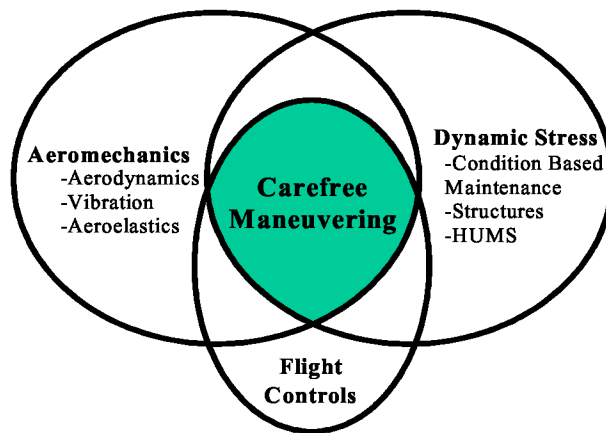
<sup>36</sup> King, D.W., Dabundo, C., Kisor, R. L., “V-22 Load Limiting Control Law Development”, 49<sup>th</sup> Annual Forum of the American Helicopter Society, May 1993.

periods of time to exploit maximum vehicle aerodynamic capabilities in the relatively rare instances when they are needed. The Vertical Takeoff Or Landing (VTOL) and hover capabilities of rotorcraft enable sustained missions in unimproved landing areas and in close proximity to both stationary and moving obstacles that involve a level of pilot situational awareness and handling qualities precision seldom required in fixed wing aircraft. Therefore rotorcraft design optimization imposes unique requirements for “Carefree Maneuvering” technology that addresses “soft” and highly dynamic limits in flight regimes where ultra-precise handling qualities and pilot situational awareness are required near envelope boundaries. The key factor needed to transition “Lines, Loads, and Laws” design practices into the rotorcraft environment is a reliable Carefree Maneuvering System (CMS) that is fully traceable to the multitude of fatigue and ultimate design loads envelopes necessary to eliminate the over-conservatism built into traditional rotary wing safe life design practices.

A Carefree Maneuvering System (CMS) recognizes aircraft limitations, both physical and operational, to allow operation within the entire flight envelope with reduced pilot workload. Rotorcraft have unique pilot workload demands because of the need to continuously monitor a large number of flight envelope exceedance potentials. The vision of “carefree maneuvering” is that inadvertent envelope limit exceedances are prevented automatically, while synergistic pilot cueing and control law tailoring allow the pilot to understand limit impingement situations instinctively and control the aircraft with confidence and precision while operating near envelope boundaries. A Carefree Maneuvering System (CMS) enables complete exploitation of an aircraft’s inherent aerodynamic capability by enabling operation in flight regimes and under real world circumstances where excessive pilot workload would otherwise limit the operational flight envelope.

As illustrated in Figure 68, carefree maneuvering will play a central role in future rotorcraft design, analogous to that played by the “Lines, Loads, and Laws” effort in commercial jet design, that eliminates many traditional design penalties in the areas of aeromechanics and dynamic stress associated with flight profile assumptions. Carefree maneuvering technology enables cross-functional optimization in the areas of vibratory loads, Health and Usage Monitoring (HUMS), and Condition Based Maintenance (CBM). Carefree maneuvering provides the capability to precisely control the envelope of the flight vehicle and hence eliminate much of the conservatism present in traditional rotorcraft design practices to account for inadvertently large and aggressive pilot inputs. Carefree maneuvering technology also provides the capability to cue the pilot to actual structural usage rates and hence eliminate much of the traditional conservatism built into safe life design methods to account for the possibility that the pilot may inadvertently or needlessly loiter in flight regimes where excessive levels of high cycle fatigue damage can occur. Fatigue damage associated with inadvertent or unnecessarily large magnitude power and/or rotor speed cycle accumulation could also be mitigated by integrating carefree maneuvering with on-line rainflow power and rotor speed cycle counting. Perhaps the greatest technology development challenge in this area is to develop the systems engineering expertise and confidence to depart from traditional conservative design practices and leverage fully the opportunity provided by carefree maneuvering technology to design rotorcraft that weigh and cost less and operate over larger flight envelopes than today’s aircraft. Carefree maneuvering offers the opportunity to manage high cycle fatigue damage related limitations in a way that makes it realistic for new rotorcraft platforms to operate in the knee of the productivity versus maintenance cost curve during real-world operations.





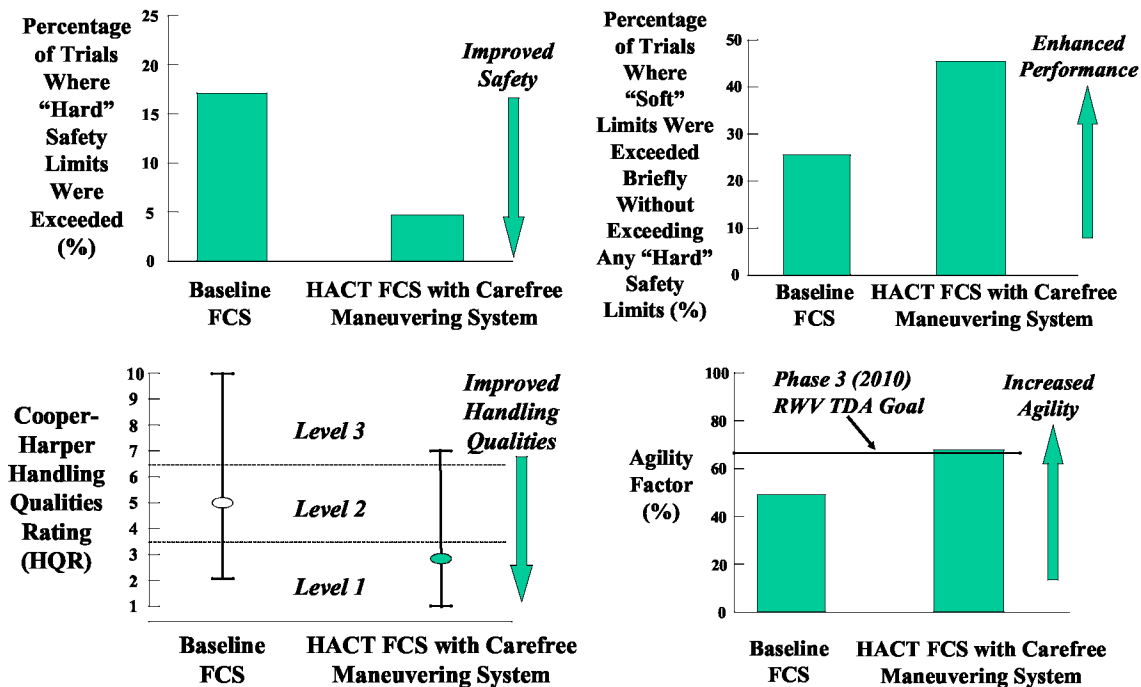
**Figure 68. Role of Carefree Maneuvering Technology in Design of Future Rotorcraft**

The U.S. Army and Boeing conducted a series of high fidelity piloted simulations under the Helicopter Active Control Technology (HACT) program that predict significant flight safety, performance, usable agility, and handling qualities benefits when a comprehensive Carefree Maneuvering System (CMS) is applied to a traditional rotorcraft such as the Apache AH-64D helicopter<sup>37</sup>. As illustrated in Figure 69, the pilot-overridable comprehensive HACT CMS reduced “hard” safety limit exceedances by a factor of 5, enhanced performance by allowing pilots to intentionally exceed “soft” structural usage related limits for brief periods of time, improved aggregate handling qualities ratings for 25 ADS-33E-PRF Mission Task Elements (MTEs) conducted in day and night conditions by at least 2 Cooper-Harper Point Ratings (CHPRs), and improved usable agility by roughly 35% in comparison to a baseline advanced Fly-By-Wire (FBW) flight control system that included non-pilot-overridable software Structural Loads Limiting (SLL) features and advanced task tailored control law modes similar to those implemented in the RAH-66 Comanche helicopter. Simulation predicts that the HACT CMS achieves the Phase 3 Department of Defense (DoD) Rotary Wing Vehicle (RWV) Technology Development Approach (TDA) maneuverability and agility sub-area goal established for the year 2010.

The HACT Flight Control System (HFCS) uses an explicit model following control law architecture integrated with Task Tailored Control Law, Carefree Maneuvering, and Regime Recognition systems. Limit prediction and tactile cueing technologies are used extensively in the HFCS to provide pilots with a “Heads-Up-Eyes-Out” operational capability that allows them to focus on aviation and scanning for obstacles during near-earth operations rather than on monitoring cockpit displays.

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<sup>37</sup> Miller, D.G., White, Elroy, and Taylor of Boeing Rotorcraft; Lukes and Gradle of McDonnell Douglas Helicopter; Segner of U.S. Army AATD, “HACT Program Technology Transfer”, Presented at the American Helicopter Society 64th Annual Forum, Montreal, Quebec, Canada, April 29-May 1, 2008.



**Figure 69. Benefits of Helicopter Active Control Technology (HACT) Tactile Cueing Carefree Maneuvering System (CMS) Predicted by Piloted Simulation of AH-64D**

The HFCS automatically addresses multiple and conflicting limit scenarios and provides the pilot with unambiguous and intuitive cockpit control tactile cue soft stops for all types of limits encountered in rotorcraft operations such as rotor stall, transmission torque, rotor speed, Turbine Gas Temperature (TGT), gas generator speed, blade flapping, power settling, and actuator rate and authority limitations<sup>38</sup>. The HFCS also includes an Energy Management system that predicts the longitudinal and lateral cockpit control positions that will result in encroachment on performance limitations such as torque, TGT, rotor speed, rotor stall, and power settling. The energy management system helps the pilot avoid entering power deficit situations where limit conflicts usually arise. The HFCS energy management system provides longitudinal and lateral control inceptor tactile cues that allow the pilot to command maximum acceleration rates subject to power limitations, maximum deceleration rates subject to rotor overspeed and power settling limitations, and maximum bank angles subject to power limitations. The energy management tactile cues are implemented through relatively mild stick force gates that allow the pilot to easily work into, around, or exceed the energy management limitations when necessary.

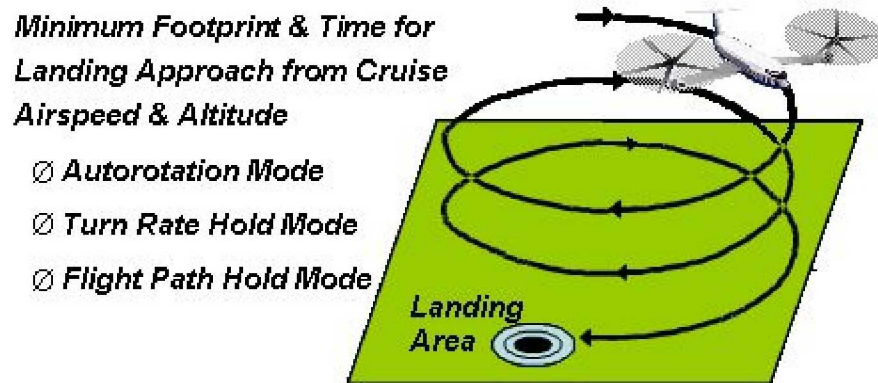
The HACT task tailored control laws significantly reduce pilot workload required to perform the curvilinear flight paths envisioned for the non-interfering approaches and departures of future civil transport rotorcraft described in Section 2. For example, the HACT control laws make it possible for pilots to perform complex maneuvers, such as the spiraling minimum footprint and time curvilinear landing approach depicted in

Figure 70, primarily through simple single axis inputs that allow the pilot to control his overall flight path precisely while scanning his surroundings in a full-time "Head-Up-Eyes-Out" manner. Similarly, the turn rate hold and flight path angle hold modes of the HACT control laws allow pilots to perform with a low level of pilot workload. Successful operation of the HACT control laws on a Joint Heavy Lift (JHL)

<sup>38</sup> Miller, D.G., Einthoven, P.G., Morse, C.S., Wood, J., "HACT Flight Control System (HFCS) Control Law Overview", Presented at the American Helicopter Society 58<sup>th</sup> Annual Forum, Montreal Quebec, Canada, June 11-13, 2002.



rotorcraft was demonstrated in high fidelity piloted simulation for the curvilinear Combat Exit and Combat Assault maneuvers under a HACT program task to assess the portability of the HFCS to tandem rotor helicopter and other helicopter platforms.



**Figure 70. Curvilinear Landing Approach Maneuver**

## **9. Selected Advanced Technologies**

This section describes the down-select process to identify those advanced technologies with the most significant potential impact to reduce the empty weight or otherwise improve the performance of civil rotorcraft. The selected technologies are quantified with brief further explanation where appropriate. Section 10 shows the net benefit of applying those technologies to both the CTR and SMRC rotorcraft concepts.

Discussions of vibration, maintenance, reliability, and health monitoring are included in this section, even though they did not quantitatively contribute to the re-sizing exercise, summarized in Section 10. Acoustics is addressed in detail in Section 11.

### **9.1. Technology Ranking Process**

There were several passes at the broad list of candidate technologies to narrow the scope to a manageable number, in lieu of investing resources to quantify them all. This included eliminating individual technologies that would only offer a very small benefit; engaging Lead Engineers and Boeing Technical Fellows in a voting approach to prioritize the list; and applying knowledge gained from the sensitivity study described in Section 7.

First, a triage process was applied to narrow the field to more meaningful candidate technologies. Some of the individual candidate technologies mentioned in Section 8 would not make significant contributions to the overall aircraft. It was not practical in this aircraft system level study to quantify the benefit of individual technologies that offered very little leverage on aircraft system level parameters, such as aircraft empty weight, performance or operating cost. Examples are given below.

- Ceramic bearings for the drive system is an example of a technology that may have significant implications in its field, for maintenance or TBO. But it represents only a tiny fraction of the total system weight and offers no significant direct impact to the vehicle system level performance.
- Individual technologies that are at very low TRL levels, such as Pericyclic and Toroidal variable speed reducers, require crude projections or outright guesses about their future weight impact, or the cost to manufacture a production version. Technologies of this kind were deemed unrealistic to include in this overall aircraft systems evaluation.
- A few of the suggested “technologies” were actually necessary design practices, such as “Design for Buffeting” and “Identify Acoustic Goals for Civil Rotorcraft”. An optimized design should account for all design criteria, so these were not technologies, per se.

However, some of the lesser individual technologies were considered as part of a larger technical group when the subject matter experts evaluated the overall future potential benefits within their discipline. This was particularly true of both the advanced structure evaluation and the advanced drive system evaluation.

Secondly, technology categories were ranked in order of potential benefit according to results from the sensitivity study (Section 7). That kept focus on those areas that had been identified to have the most potential payoff, even though the sensitivity study was itself conducted from a best guess of possible improvements before the technology benefits were actually quantified. The Principal Investigator (PI) and Associate Investigator (AI) weighted the final ranking, considering the importance of the Success Criteria set forth in Section 1.3. That included goals of high availability, low maintenance, low vibration and noise for the passengers, and acceptable external noise in terminal areas.

Next, the popular vote from a group of thirteen Lead Engineers and Boeing Technical Fellows produced the ranking within each category, based on the experience of those subject matter experts. This group covered the specific disciplines of rotor design, dynamics, drive system, structures, aerodynamics, and acoustics. Generally, the Lead Engineers voted within their discipline, while the participating Technical Fellows and Chief Engineer voted in any discipline they chose to.

## **9.2. Ranked List of Technologies**

The candidate technologies were discussed in Section 8. The final list of grouped and ranked technologies is shown in Table 21. A total of 16 categories were defined. The green and white bars only signify separation between the groups.

The PI and AI selected specific technologies from Table 21 to be applied to the CTR and SMRC aircraft to determine their net weight and cost benefits. Those technologies were subsequently quantified. We learned during the above process that group benefits were more easily applied than many small benefits. An analogy can be drawn to a diversified investment fund that banks on having some winning investments (technologies) out of a group, and avoids risking everything on a single super-star.

Technologies from eleven categories out of the list of sixteen were quantified and applied in successive resizing of the SMRC and CTR rotorcraft. These quantified technologies were all applicable to both rotorcraft concepts, albeit to different degrees. So the “Application Matrix”, originally intended to tie each technology to a rotorcraft concept, was found unnecessary. The selected technologies are identified and quantified in the following sections.

Five categories of the sixteen were not quantified, although they too are essential for civil rotorcraft to achieve economic viability, passenger acceptance, and safety. A combination of high utilization and low maintenance are needed for a successful civil transport rotorcraft. Passenger and community acceptance are also essential, requiring low vibration levels, relatively low interior noise levels, and reduced external noise for community acceptance. Thus, maintenance, dynamics, acoustics, vibration, and advanced flight controls are each discussed, but were not quantified or included as the CTR and SMRC rotorcraft were resized with the other advanced technologies.

## **9.3. Net Benefits of Major Technology Groups**

### **9.3.1. Advanced Engine Technology**

Section 8.1 described several advanced engine technology programs. The goals of these programs have provided both the direction and funding to make major strides toward lighter, more efficient engines with lower maintenance. Test cell demonstrations have proven the merit of such programs, but few of the benefits are seen in a new production engine, leaving questions about when the performance potential may be realized in a production engine.

**Table 21. Candidate Advanced Technologies In Rank Order**

Rank	Category	Candidate Advanced Technologies	Addressed
1	Engine Fuel Flow	Reduced Engine SFC Higher contingency power rating for FAA Category A takeoff. Engine cycles tailored to cruise conditions.	✓ ✓ /
2	Structure Weight	Advanced Materials for Lighter Structure Structural Analysis for Lighter Structure Advanced Airframe Structural Design Concepts & Manufacturing (optimized for local loads)	✓ ✓ ✓
3	Drag	Thinner wings to reduce compressible drag. CFD - optimization to reduce Fuselage and interference drag. Parasite Drag Reduction Sails on outboard nacelle panels to reduce drag. Select SMRC RPM / thrust to maximize total aircraft L/D	✓ / ✓ / /
4	Rotor Cruise Performance	Advanced passive blade design for CTR cruise efficiency Optimize SMRC propeller planform, airfoils, rpm & twist for cruise efficiency.	✓ /
5	Reduced Maintenance	IVHM Tool Infrastructure / support system	✓ /
6	Drive System	Transmission Configuration Advanced Components Advanced Materials & Processing Further Investment Development Tool Infrastructure / support system (see above) 2-Speed Transmission Variable Speed Drives	✓ ✓ ✓ ✓ ✓ ✓ /
7	Rotor Hover Performance	Advanced passive blade design features for hover performance. Reconfigurable Rotor Blade (RRB). Effect on hover FM	✓ /
8	Dynamics	Air resonance, Ground Resonance, Active stabilization Design rotor hub and wing for whirl flutter and less weight. Effect on Rotor weight Gust alleviation	Stiff In-plane ✓hub (CTR) /
9	Acoustics	Identify acoustic goals/constraints for terminal approaches to major airports (and units) Identify cabin acoustic goals for Civil Rotorcraft acceptance. BVI noise reduction with active tip wake vortex dissipation, or active blade control.	✓ / ✓
10	Rotor Control of Noise & Vibration	Individual blade control (IBC) to reduce noise and vibration (active pitch links or on-blade pitch control (no swashplate)). Active control of blade aerodynamic lift and pitching moment loads (active blade TE flap). Variable-span morphing rotor blades.	Yes ✓ /
11	Flight Controls	Affordable Fly by Wire controls Sensors/Control laws for carefree maneuvering (HACT)	/
12	Active Vibration Control for Cabin Comfort	Active cabin vibration reduction systems. Vibration reduction at the source with more blades. Metric and goal for vibration comfort level. Active vibration control on the rotor	✓ ✓ ✓ *SMART* Rotor
13	Download	Active Flow Control to reduce hover download on wings and fuselage.	✓
14	Fixed Equipment	Weight reduction of "systems", i.e. electrical, hydraulic, avionics, ... Weight reduction technologies for cabin furnishings (e.g., passenger seats).	✓ ✓
15	Rotor Hub, Pylon, & Nacelle Drag	Spinner/hub design to reduce CTR drag. Active Flow Control (AFC) to reduce drag of rotor hub fairing, pylon, engine nacelles.	/ ✓
16	Rotor System Weight	Blade weight reduction. Hub Weight reduction.	✓ ✓

## Fuel Flow

The goal of a 35% reduction in specific fuel consumption (SFC) relative to the AE1107C, scaled up with horsepower is shown in Figure 71.

A Boeing propulsion engineer surveyed the status of the advanced engine programs and made a “best guess” for performance benefits in a production engine for the 2020-2030 time frame, shown by the line marked as “20.5% SFC Improvement”. While more aggressive positions could be taken, this was the level of advanced engine technology applied in both the SMRC and CTR evaluations.

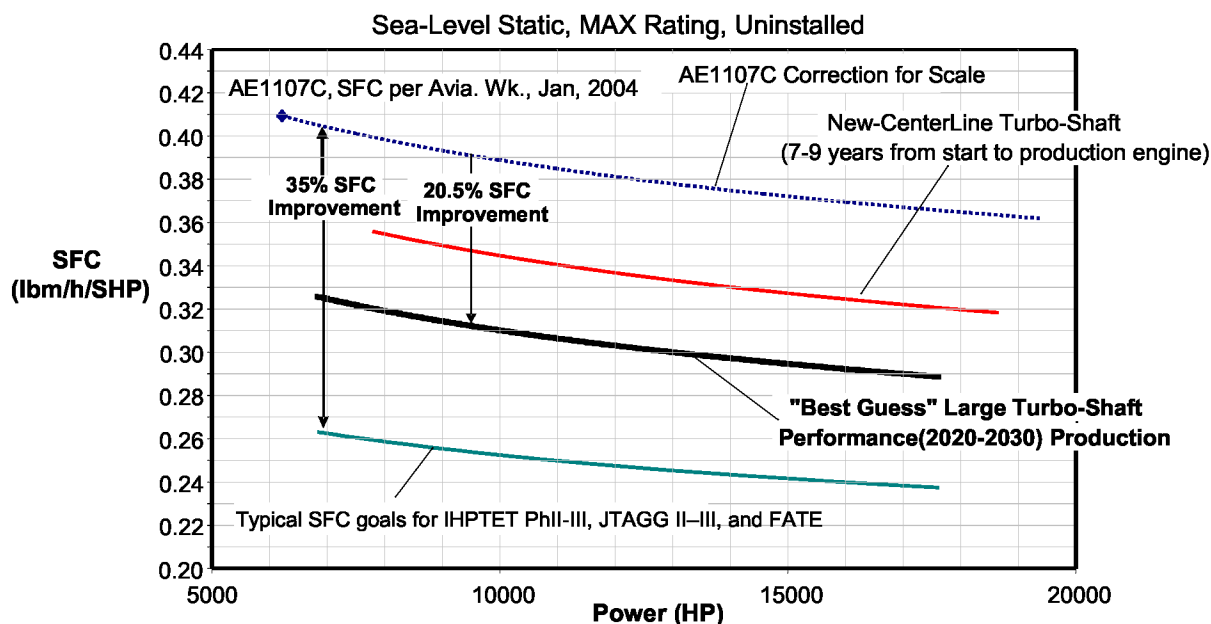


Figure 71. Trend of Advanced Engine SFC Versus Power

## Contingency Power

The FAA Category A OEI requirement for civil transport rotorcraft stipulates (in brief) that the rotorcraft must be able to safely return to the takeoff pad following an OEI event occurring prior to reaching the Critical Decision Point (CDP) along the takeoff flight path. Or, it must be able to continue flight following an OEI event occurring after the CDP, establishing specified minimum rates-of-climb and then steady flight at the takeoff safety speed.

Section 6.3.3 identified three possible means of satisfying the Category A requirement. The most attractive is believed to be a contingency power of 10% to 15% beyond the engine's max takeoff power. Contingency power would be rarely used, if ever, but allows the engine to operate at normal power ratings for efficient cruise fuel flow for most of the life of the engine. Fuel consumption during an OEI event is of no importance.

The alternative is to oversize the engines to provide the power needed for recovery from an OEI event when one engine is inoperative. That alternative means the engines are always operating well below the normal rated power in cruise with a correspondingly higher SFC.

## Power Density

A major goal of the several advanced engine programs has been to increase the HP/weight of the engine, i.e. its power density. The goal of IHPTET PhII was a 120% increase in power density and the

current VAATE program goal is a 90% increase (relative to different reference engines). These dramatic benefits can have nearly as much impact on the bottom line as the improved SFC, whether that's more tonnage, more troops, or longer range.

The FATE program goal of 35% reduction in SFC would save 3500 lb of fuel on the baseline CTR. The FATE goal of a 90% increase in power density would reduce the empty weight by 2130 lb, from both the engine weight and engine installation. And while the fuel savings lets the aircraft down-size, only the reduced engine weight changes the empty weight directly and reduces the EW/GW ratio.

### 9.3.2. Advanced Structures Technologies for SMRC Helicopter

Advanced structures technologies were described in Section 8.2. The potential benefit of structural weight reduction was found to be substantial during the sensitivity study, so special attention was given to quantifying these benefits for the SMRC and CTR vehicles. Estimates of structural weight reduction for the SMRC and the CTR were performed separately, but collaboratively, and are detailed below.

A preliminary analysis of the primary structure was conducted on the SMRC helicopter concept design to determine the feasibility and potential weight savings of applying tape laminate and core to the primary structure of the aircraft. This analysis was not intended to establish structural adequacy. The following paragraphs provide highlights of that analysis. Details of the analysis are in Appendix B.

#### Wing

The load diagram shown in Figure 72 was the basis for estimating the weight savings of primary wing structure for the SMRC concept. Material properties and allowables for carbon tape and core were applied in this analysis. Ultimate loads were based on a factor of safety of 1.5 at a 2.5g flight condition

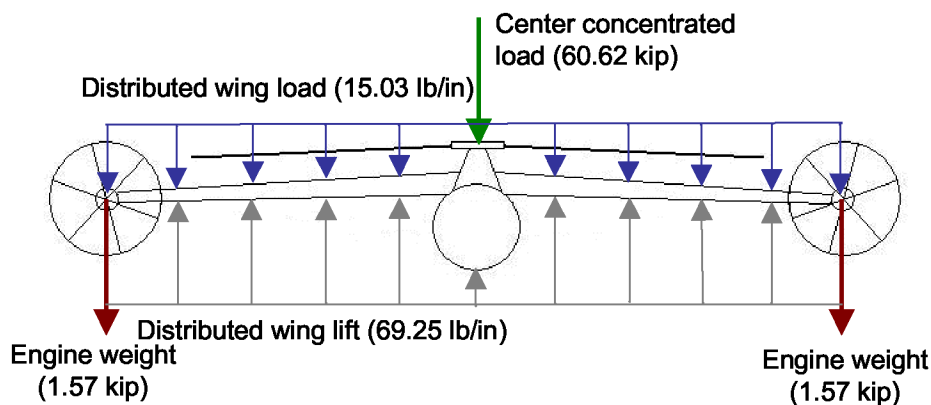


Figure 72. Structural Load Diagram For SMRC Configuration

#### Fuselage

The fuselage skin was analyzed for pressure loading and fuselage bending. Pressure loading, was for an internal cabin pressure equivalent to 7,000 feet (11.4 psi) operating at a maximum flight altitude of 30,000 feet (4.4 psi), resulting in a pressure load of 7.0 psi. A factor of safety of 2.0 was included in the pressure loading calculations

A minimum required skin thickness was determined for pressure loading (90°-fiber direction) and fuselage bending (0°-fiber direction), and a distribution of ply count was developed including +/- 45° plies. A 1.0 inch core was assumed for local stability to the skin, as well as thermal and acoustic insulation. The total weight of the fuselage skin was determined to be 3537 lb.

Frame weight was estimated, based on an estimate of 45 primary frames with a pitch of 24 inches between frames. The total weight of the frames was 286 lb.

### Wing Box

The shape of the wing box cross-section was assumed to be rectangular with a constant wing thickness ratio of 0.18. The minimum required thickness of the cap and web were determined for bending and stability. The shear and moment at the wing-to-fuselage joint and wing tip were applied in the analysis. Primary structural weight of the wing was estimated to be 2502 lb.

The wing-to-fuselage joint was also analyzed to determine the number of fasteners required. Based on the web geometry, assumed fastener diameter and allowable bearing stress, two rows of 15 fasteners would be required.

### Summary

The preceding analysis is assumed to account for 50% of the fuselage structural weight, and 40% of the wing structural weight. The remaining weight includes all secondary structure, such as doors, panels, windscreens, bulkheads, floors, wing leading and trailing edges, and control surfaces. A summary of the estimated primary structural weights and their application to the SMRC resizing is shown in Table 22. The result was a 20% reduction in primary structural weight, equating to a 10% reduction for the total fuselage weight and a 8.1% reduction for the total wing weight.

**Table 22. SMRC Weight Reduction With Advanced Structures Technologies**

Structure	HESCOMP Prediction* (lb)	% of Primary Structure	Primary Structure (lb)	Estimated for SMRC (lb)	Savings
Fuselage	9522	50%	4761	3823	20%
Wing	7857	40%	3143	2502	20%

The analysis shows the potential for weight savings and feasibility of designing with laminate and core technology to the primary structure of the aircraft. The analysis is meant to serve as an indicator for the potential of such methods, not to establish specific design criteria or structural adequacy.

### 9.3.3. Advanced Structures Technologies for Civil Tilt Rotor

This section describes the methodology used to derive a final estimated primary and secondary structures weight for the civil tilt rotor aircraft with the impact of advanced structures technologies in the future (~20 years). Primary structures include the wing, body, tail, rotor, nacelles, & landing gear, while secondary structures consist of fairings, access panels, landing gear doors, etc.

Section 8.1.2 described many of the candidate advanced technologies for structure, but the judgment of where these advanced technologies apply cannot be made across a whole weight group, such as the body or the wing. These judgments must be made at a sub-group level. For instance, thermoplastics may be ideal for components such as cowlings or access panels, but not suited to primary load-bearing structure. VASCOMP weight estimates are for the whole body and the whole wing, so a means was devised to break those estimates into the needed sub-groups, determine the benefit of advanced technology at the sub-group level, and then recombine to arrive at a net benefit to the VASCOMP weight group. The methodology utilized weights and structures data from V-22 to calculate factors that were then applied to similar data from a CTR VASCOMP sizing case.

The process began with a detailed list of V-22 component weights, organized by structures groups similar to those of the VASCOMP groups (e.g., wing, rotor, fuselage, body, tail, & engine), and removing the military components (e.g. rear ramp, wing stow, blade fold, sponsons, external hooks and cargo handling). These military weights were subtracted at the sub-group level to obtain values for a 'civilianized' V-22. The 'civilianized' weight data was used to define fractions of the sub-groups based on the V-22 weights. For instance, the wing group weight was broken into basic structure, secondary structure, and control surfaces, and the body group was broken into basic structure, secondary structure (nose cone, windshield, windows, flooring, lightning strike), and a sub-group of doors, ramps and panels.

A judgment was made on the percent weight improvement that advanced structures technologies would bring to each sub-group of each weight group. The results were rolled back up to group levels and are summarized in Table 23.

The advanced structures technologies were grouped as either: Materials, Manufacturing Technology, or Design & Optimization. Each technology group was then evaluated for its potential impact to weight reduction compared to its category peers and assigned a percentage factor. Overall group percentages were rolled up from the sub-groups. The weight reduction from each technology group was applied to the “Group % of Baseline Structure Weight” values to derive the “Weight Group Reduction, % of Group Baseline” in Table 23. These values are the estimated potential net weight benefit of advanced structures technologies on each CTR structure weight group.

The last column shows the potential structural weight savings of each weight group as a percent of the total structural weight. For instance, a 13.9% weight reduction is shown for the wing, which itself is 29% of the total structural weight, giving a 4% reduction relative to the total structural weight.

Table 23 shows that advanced structures technologies have the potential to reduce CTR structural weight by 17.8%, relative to the baseline CTR.

**Table 23. CTR Weight Reduction With Advanced Structures Technologies**

Weight Group	Group % of Baseline Structure Weight	Advanced Structures Technology Group			Weight Group Reduction, % of Group Baseline	Weight Group Savings, % Structural Weight
		Materials	Manufacture Technology	Design & Optimization		
WING GROUP	29.0%	5.2%	2.1%	7.4%	13.9%	4.0%
ROTOR GROUP	26.6%	3.4%	2.4%	7.3%	12.7%	3.4%
TAIL GROUP	2.8%	8.6%	4.8%	6.5%	18.7%	0.5%
BODY GROUP	25.1%	11.8%	3.3%	7.6%	21.0%	5.3%
LANDING GEAR GROUP	4.4%	5.4%	8.9%	19.3%	22.1%	1.0%
ENGINE SECTION OR NACELLE	10.1%	9.4%	5.6%	11.7%	18.7%	1.9%
STRUCT WEIGHT INCREMENT (WINDOW BELT)	1.9%	80.0%		50%	90%	1.7%
<b>TOTAL STRUCTURE WEIGHT</b>	<b>100.0%</b>	6.8%	3.2%	8.2%		<b>17.8%</b>

#### 9.3.4. Advanced Drive System Technology

Advanced drive system technologies were presented in Section 8.3. In total, they have the potential to reduce drive system weight by up to 30% for a single-speed drive system. Dual-speed transmissions, as



required by the SMRC or a tilt rotor that requires a large RPM reduction for cruise, would suffer an 8% increase on the basic transmission, yielding a net 22% overall reduction in drive system weight.

Table 24 summarizes the estimated potential benefits of five drive system technology groups to the drive system weight, costs, and acoustics.

Drive System Technology		Component Weight Benefit	Overall Drive System Weight (cum)	Development Cost	Production Cost	Support Cost	Acoustics
<b>Net Overall Benefit</b>		- 30 %	+35%	+15%	- 30 %	- 15 dB	
<b>System Level - Configuration Dependent Technologies</b> such as Double Helical planetary output, and Split Torque	-12.0%	88.0%	+5%	-5%	0.0%	-5, -10 dB	
<b>Advanced Component &amp; Subsystem Technologies</b> such as Hybrid Ceramic Bearings and Adv Tech Bearings	-4.0%	84.0%	+5%	+5%	0.0%	-5 dB	
<b>Advanced Materials &amp; Processing Technologies</b> such as Light metal planetary carrier and accessory gear/spine	-6.0%	78.0%	+5%	+5%	-5.0%	0.0%	
<b>Composite main rotor shaft, and cross-shaft segments</b>	-8.0%	70.0%	+10%	0.0%	-5.0%	0.0%	
<b>Tool Infrastructure and Support System Technologies</b> such as Vibration Reduction, and Adv Torque sensor monitoring	0.0%	70.0%	+10%	+10%	-20%	-5, -10 dB	
<b>Variable Speed Transmissions</b>	+8%	+8%	+10%	+10%	+5%	-5, -10 dB	

**Table 24. Summary of Advanced Drive System Technologies**

### 9.3.5. Advanced Rotor Blade and Hub Technology

Advanced rotor blades and hubs are generally driven by improvements in advanced materials. Section 8.5.1 described the multitude of requirements that a rotor blade must meet. It concluded that blade weight could conceivably be reduced by 20% by 2023, and meet all design requirements for safe and reliable operations. This potential could be confirmed by assuming improved material allowables and then designing a blade, but that was clearly out of scope for this study. Consequently, a 15% reduction in blade weight was assumed as a feasible target over the next 15 years.

Several advanced technologies were mentioned in Section 8.5.2 with the potential to reduce the weight of rotor hubs. Of course, a blade weight reduction will itself allow a lighter hub weight, but that is already accounted for in the VASCOMP sizing code. The weight of hub components may be reduced by 15% to 30% by substituting parts manufactured with nanotechnology, carbon fiber, or metal matrix composites. Section 8.5.3 also referred to advanced hub concepts, such as a hub design with a single elastomeric bearing for each blade that could reduce total hub weight by 10% to 15%.

A conservative 7% weight saving for the hub was used to represent advanced hub technology 15 years from now. Even that may be a stretch, since hub designs and weights have not changed much over the past 15 years.

### **9.3.6. Advanced Airframe Performance**

Airframe performance covers hover download and cruise drag for purposes of this study. Because of the different characteristics of the SMRC and the CTR, each concept's performance is evaluated separately.

#### **SMRC Rotorcraft**

The sensitivity study of the baseline SMRC, described in Section 7.1, showed that a 5 count reduction in the SMRC hover T/W ratio, such as from 1.13 down to 1.08, reduced the SMRC \$DOC/ASM by 3% and reduced the empty weight by slightly over 1%. The DOC/ASM metric is more a reflection of fuel demand in this instance, as the cost of fuel dominates the DOC. A reduced T/W ratio requires less installed SHP and gives a better power match for cruise, resulting in slightly less fuel consumption. An assumed 7 count increase in hover Figure of Merit (FM) gave a 3% reduction in both \$DOC/ASM and in empty weight. The improved hover performance from FM and T/W resulted in a smaller engine, but the engine weight is only about 4% of GW, so there was a moderate impact on total empty weight.

Reduced parasite drag in cruise was found to be more beneficial than improved hover performance. When parasite drag was reduced by 20% in the sensitivity study, it reduced the SMRC \$DOC/ASM by 4% and the empty weight by 6%. The reduced mission fuel (from reduced drag) had a strong effect, as fuel was about 10% of GW. The benefit was amplified by aircraft down-sizing as a result of less mission fuel required. So it is not surprising that 20% drag reduction effecting fuel had more influence on empty weight than a 5 count reduction in hover download that reduced installed power.

The three performance technologies of hover FM, T/W ratio, and parasite drag significantly effected the SMRC when taken together.

Active flow control, described in Section 8.6.5, offers both reduced wing drag and reduced hover download, when correctly applied on the applicable surfaces. Advanced AFC technology has the potential to reduce hover download by 25%.

Estimated drag of the rotor hub, pylon, and interference between the two, is one-half of the total estimated parasite drag of the SMRC rotorcraft. Test experience with application of AFC to bluff aircraft components, such as a rotor hub and pylon, indicates that drag reductions of up to 50% could be achieved by applying AFC in a very tailored manner to the pylon and the upper fuselage and wing area near the pylon. This would require an analytical and experimental development of the AFC configuration; including a multi-entry, medium-to-large-scale, wind tunnel test series. A 50% reduction in parasite drag was taken for the SMRC rotor hub and pylon region, assuming application of advanced AFC, yielding a 25% reduction in overall parasite drag for the SMRC.

The weight penalty for AFC devices, their air source and air distribution system is expected to be small, but was not assessed in this study. The tasks associated with integrating the AFC system into the aircraft design is probably not so small, and failure modes and consequences depend on the AFC implementation.

#### **CTR Rotorcraft**

The baseline CTR sensitivity study (Section 7.2) showed a 5 count reduction in hover T/W produced only a 1% reduction in \$DOC/ASM and about a 2% reduction in empty weight. And a 7 count increase in Figure of Merit gave about 1% reduction in \$DOC/ASM and 2% reduction in empty weight. The CTR engines were sized by cruise in most cases, not by hover, which explains why the CTR was only half as sensitive as the SMRC to download reductions and increased FM. An assumed 20% reduction in CTR parasite drag gave a 7% reduction in the CTR \$DOC/ASM, and a 3% reduction in empty weight,

indicating it has a higher sensitivity to parasite drag than the SMRC. This is partly due to the 305 knot design cruise speed in comparison to the SMRC 250 knot cruise speed (power required goes as airspeed cubed if other factors are equal). And it is partly due to the difference in the baseline engine SFC between the two rotorcraft. The SMRC baseline SFC was about 9% less than the CTR, making the CTR mission fuel somewhat more sensitive to changes in parasite drag.

AFC has an excellent potential to reduce wing download on the CTR. The baseline hover download was 10.3% of thrust. A 24% reduction was taken for application of AFC to the wing flaps, yielding a download of 7.8% of thrust for the advanced configuration.

The CTR took a general 16% reduction in parasite cruise drag, plus benefits from reduced excrescence, interference, and momentum drag. High-fidelity design technology can achieve this by optimizing the design of the wing, airfoils, and wing-body juncture through CFD analysis, rather than assume the benefits from AFC. The wing C<sub>do</sub> was reduced an additional 10% for reduced wing thickness ratio. Table 25 compares the baseline CTR parasite drag to the advanced drag.

**Table 25. Comparison of CTR Baseline and Advanced Parasite Drag**

Item	Baseline	Advanced
Wing Thickness Ratio	0.23	0.20
Relative discrete roughness	1.0	0.50
Fuselage fe, ft <sup>2</sup>	10.0	8.4
Wing fe, ft <sup>2</sup>	10.8	8.2
Empennage fe, ft <sup>2</sup>	2.4	2.02
Engine/ Rotor Nacelles fe, ft <sup>2</sup>	3.7	3.1
Miscellaneous fe (AC, Momentum, Trim), ft <sup>2</sup>	1.2	0.8
Subtotal, ft <sup>2</sup>	28.1	22.5
Excrescence Factor	x 1.07	x 1.04
Total fe, ft <sup>2</sup>	30.07	23.4

### 9.3.7. Advanced CTR Rotor Design

The unique inverse inboard taper of the advanced CTR rotor blade and the airfoil and twist distributions were shown in Figure 60, as designed for a 350 knot airspeed at 24,000 ft altitude with a 600 fps rotor tip speed. The rotor design Ct/σ was 0.133, with a 0.112 solidity. Hover performance of the advanced CTR rotor design was shown in Figure 61, achieving a peak hover FM of 0.75 at a Ct/σ of 0.13, close to the design Ct/σ. The hover Figure of Merit improvement was a fallout from the advanced CTR rotor design

A 600 fps cruise tip speed was selected for the advanced CTR rotor blade to stay within a helical tip Mach number of 0.825. Rotor cruise propulsive efficiency was 0.84 at the design airspeed of 350 knots and 80% cruise rpm (600 fps/ 750 fps), as shown in Figure 62. Cruise propulsive efficiency remained above 0.80 up to 385 knots.

### 9.3.8. Advanced SMRC Rotor Design

The baseline SMRC rotor design was presented in Section 6.1.2 and Section 8.6.4. The baseline hover Figure of Merit was shown in Figure 21 and the rotor cruise L/D<sub>e</sub> was shown in Figure 22 and Figure 23. The SMRC rotor is unloaded in high-speed cruise to only 10% of 1g lift, with the wing carrying 90%. A critical aspect of the SMRC rotor is the ability to maintain near zero hub moments and minimum flapping during cruise. Carrying 10% of the lift helps the rotor maintain zero hub moments. A second critical aspect is that it should produce low drag. The low blade twist and thin outboard airfoils contribute to low cruise drag.

Proposed advanced technology for the advanced SMRC rotor were outlined in Section 8.6.4. They are focused on hover performance, as the installed power and main transmission rating are sized by the hover condition. A combination of blade tip anhedral, 6° more twist, and non-linear twist are expected to add 8% to the hover Figure of Merit.

Additional advanced technologies will be required to control blade flapping and reduce vibratory loads during high-speed cruise. The SMART rotor concept, described in Section 8.6.2 may be able to achieve this by tailoring the airloads with azimuth at frequencies greater than 1/rev.

### 9.3.9. Dynamics Technology

#### Structural Dynamics

Dynamics is a major technical discipline for rotorcraft. Hub loads from vibratory blade loads drive the hub design, and those vibratory loads passed from the rotating system to the fixed system drive the fuselage and cabin vibration environment. Several items suggested for the original list of technologies were actually requirements, not technologies contributing a solution. These included designs for air resonance, ground resonance, active stabilization for dynamics, and a rotor hub and wing design for whirl flutter.

The rotor hub concept and design are fundamental to avoid tilt rotor whirl flutter. The chart below was extracted from rotor and dynamic studies conducted in the 1990's, Figure 73. It compares calculated wing damping for a gimbaled rotor with a fundamental flap frequency of 1/rev, to that of a Semi-Articulated Stiff InPlane (SASTIP) rotor hub concept with a fundamental flap frequency of 1.2/rev. The gimbaled rotor showed reduced stability beyond 280 to 300 ktas and went unstable beyond ~340 ktas, whereas the SASTIP rotor maintained high damping and was stable beyond 350 ktas. The stiff inplane hub also avoids ground resonance.

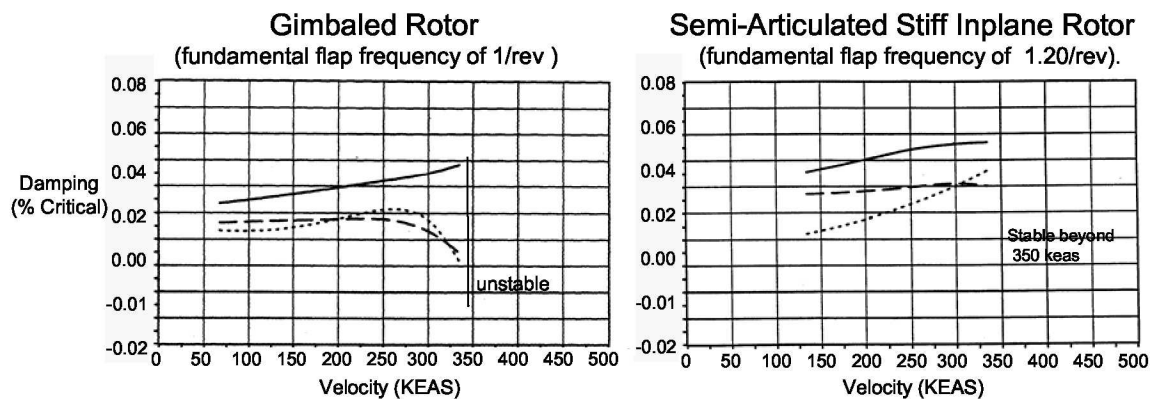


Figure 73. Whirl Flutter Damping of Two Hub Types

However, the SASTIP hub concept also requires high flapping frequency to avoid large coriolis forces on the stiff inplane blades. That would limit blade flapping and therefore the ability to provide adequate yaw control for the tilt rotor when in helicopter mode hover. That restriction may necessitate nacelle tilt in hover that follows pilot commands for yaw.

Increasing lift curve slope with Mach number is another major contributing factor to whirl flutter instability. This destabilizing effect near the blade tip is alleviated by reduced tip speeds in cruise, and by the tapered outboard planform proposed in the advanced CTR rotor design. While not a solution in itself, it is a contribution.

Dynamics and vibration of the SMRC rotor at its cruise advance ratio of 0.77 were not addressed. Tech-02 analysis indicated the rotor could be trimmed to zero hub moments, but dynamic response to gusts and stability were not evaluated. This area requires further investigation, both analytical and with model-scale wing tunnel testing.

## **Vibration**

The vibratory environment encountered in a rotorcraft has a major impact on its usability characteristics, i.e., the ability of the crew to perform the mission, the ride quality for the passengers, as well as the reliability and life of avionics, the fatigue lives of the airframe components and equipment, and the operational envelope in terms of GW, speed, altitude, and maneuver capability. Most of today's helicopters have practical speed limitations well below their power limits because of uncomfortable vibrations. Helicopter vibrations tend to rise while departing from hover through transitional flight (and flare entering a hover), then reduce as speed increases to the minimum power condition and then generally deteriorate again with further increasing speed and power. Today, vibration control is achieved primarily through passive and active vibration treatment, which can weigh as much as 4% of design gross weight—a generally unacceptable weight penalty.

No single approach has been found that offers a total solution to low cabin vibration, but many have been tried and found very effective. The truth is that cockpit and cabin vibration environments of most large helicopters would be far beyond human comfort zones without vibration treatment. Published International Standard ISO limits for vibration are shown in Figure 74 versus frequency<sup>39</sup>, including the Exposure Limit Boundary (ELB), the Fatigue and Decreased Proficiency Boundary (FDPB), and the Decreased Comfort Boundary (DCB). Goldman Rankings are also shown,<sup>40</sup> as are reference lines for current Turboprops and Turbofans.

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<sup>39</sup> International Standard 2631, Second Edition -1978-01-15, 1978.

<sup>40</sup> Design, Development, and Flight Testing of the active vibration control system for the Sikorsky S-92, Robert Goldman, Tom Millot, AHS 56th Annual Forum, May, 2000

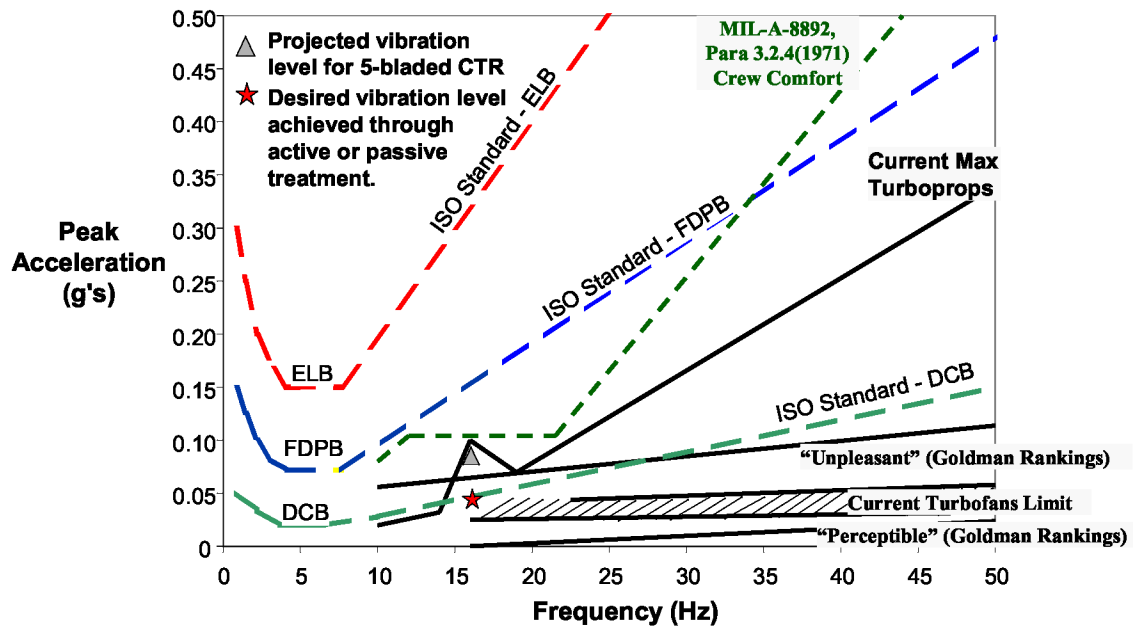
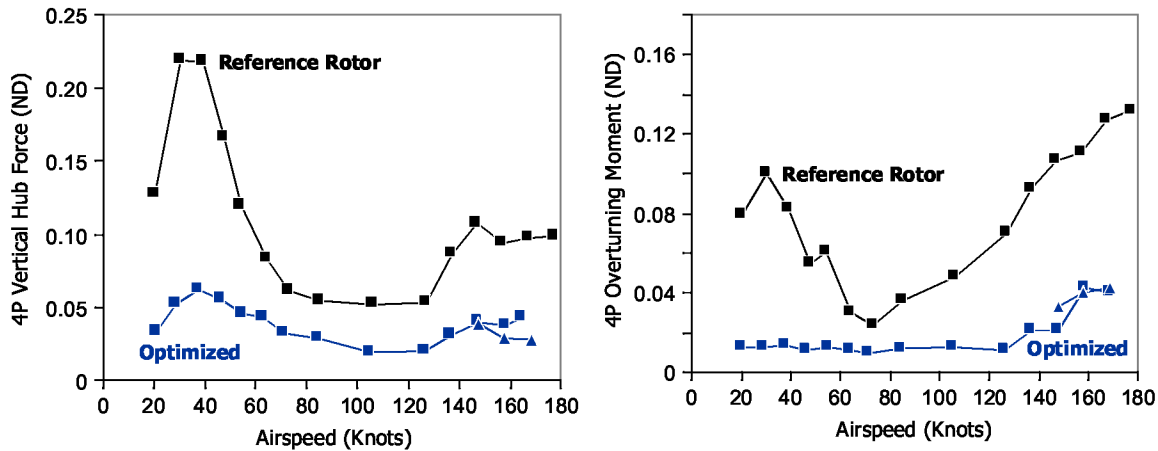


Figure 74. Vibration Design Criteria

Obviously, a civil rotorcraft should fall below the DCB line. A 5-bladed 60 ft diameter CTR rotor operating at 600 fps tip speed would have a frequency of about 16 Hz, requiring peak accelerations under 0.05 g's to meet the DCB objective. That would also place it in the upper portion of the Turbofan band, a good indication of the objective's validity, and its difficulty, i.e. the goal of a "Jet Smooth Ride".

The larger diameter SMRC rotor, operating at a tip speed of 546 fps (84% N2) would have a dominant frequency of 10.3 Hz, in the frequency range where human sensitivity is the greatest. This would appear to require very low peak accelerations, on the order of 0.025 g's. It must also be acknowledged that 4-bladed tilt rotors of CTR size with cruise tip speeds less than 550 fps would also fall in this low frequency band (< 11.7 Hz). This consideration could ultimately drive both the CTR and the SMRC to more blades, at the expense of increased rotor system weight.

Achieving these vibration goals will require multiple technologies, including reduced vibrations from the rotor, de-tuned fuselage structure, and active cabin vibration reduction devices in the fuselage. One approach to reduce vibration is to optimize structural properties to produce a low vibration rotor design. Aeroelastic optimization schemes can be employed for systematically altering structural blade properties. Such an approach has been applied to the design of two different Mach-scaled, four-blade, fully-articulated, ten-foot diameter wind tunnel rotors. Each design was fabricated and tested in the Boeing V/STOL wind tunnel. The goal was to develop a rotor that would substantially reduce the fixed system 4P vertical hub loads and the fixed system 4P roll and pitch (overturning) hub moments. Accomplishing this goal required the design and fabrication of three rotor blade sets for the CH-47: a low vibration rotor (LVR), and an improved low vibration rotor (ILVR). As shown in Figure 75, the resulting 4P vertical hub load and 4P overturning hub moments are significantly reduced throughout the measured airspeed range, validating the passive design aeroelastic optimization methodology.



**Figure 75. Measured 4P Vertical Hub Loads and Hub Moments Reductions**

New rotor system concepts may help achieve low vibration goals, such as active control of the blade aerodynamic lift and pitching moment loads using an active trailing edge flap (i.e. the SMART rotor concept), and individual blade control (IBC) that allows introduction of higher harmonic control of blade pitch. Boeing has developed a full scale Smart Material Actuated Rotor Technology (SMART) system with piezoelectric actuated blade flaps. The development effort included design, fabrication, and component testing of rotor blades, trailing edge flaps, piezoelectric actuators, switching power amplifiers, and the data/power system. Simulations, model scale and full scale wind tunnel tests have shown that this system can provide 80% vibration reduction. Testing of the 34-foot diameter rotor demonstrated the functionality, robustness, and required authority of the active flap system. Ultimately, these devices would be driven by sensor feedback allowing real time adjustment.

#### **9.3.10. Advanced Flight Controls Technology**

Any future CTR or SMRC will leverage full authority Fly-By-Wire (FBW) Flight Control System (FCS) technology to maximize vehicle productivity, flight safety, and flight path command precision while minimizing pilot workload.

Several individual features of the HACT CMS have been transitioned into the production CH-47F Chinook and V-22 Osprey programs and shown to provide significant benefits through flight test and operational evaluation. The successful transition of individual carefree maneuvering and task tailored control algorithms developed under the HACT program into the production CH-47F Chinook and V-22 Osprey fleets provides a high degree of confidence that a full authority Digital FBW FCS with integrated Regime Recognition, Task Tailored Control Law, and Carefree Maneuvering functional elements will be a pivotal enabling technology for future rotorcraft such as the CTR and SMRC.

The advanced flight controls described in section 8.8 may eventually become de facto standards. It is clearly an enabling technology for civil rotorcraft. But without a discernable effect on weight, or performance, or cost, they were not quantified or included in the subsequent rotorcraft sizing.

#### **9.4. Health Usage Monitoring Technology**

This technology has made great advances in the past 15 years. It is found in various forms on several production helicopters and the U.S. military has begun implementation as well.

A Honeywell EVXP Health and Usage Monitoring System (HUMS) was certified by the Federal Aviation Administration in October of 2007 and was selected by Sikorsky Aircraft Corp. as a standard option for the S-76C++™ helicopter. The following is paraphrased from an article in the HELITECH, United Kingdom, October 03, 2007

*The Honeywell advanced, fourth-generation system monitors aircraft vibration, engine and structural health and works with ground support equipment and software to decrease maintenance costs and increase operational readiness. Honeywell's EVXP is designed to meet the demanding operational and regulatory requirements of helicopters supporting offshore oil and gas producers (OGP). It also meets European operating standards.*

*Honeywell's Rotor Track and Balance (RT&B) solutions provide a smoother operation, minimize vibration, and extend the maintenance life of various critical helicopter components. The EVXP system includes on-board sensors and a data processor to calculate specific maintenance solutions using proprietary algorithms. It builds on the success of Honeywell's VXP system, the most widely deployed onboard HUMS product in the commercial helicopter industry.*

Boeing's Integrated Vehicle Health Monitoring (IVHM) program integrates system health data into operational decision-support information that can play a major role in the management of a system's operations and cost. It is necessary to understand a system's operational and cost drivers, the resulting benefits, and the life cycle costs for implementing IVHM.

Boeing's IVHM Program Analysis process provides a method of identifying solutions and evaluating the financial and operational benefits of these solutions. This process includes Affordability Analysis to identify where IVHM solutions should be implemented to maximize the benefit within the customer's requirements, Concept of Operations Analysis to define the operational implementation of IVHM and the resulting operational benefits, and Business Case Analysis to quantify the life cycle cost impacts of a solution. In addition to these processes, Boeing has developed a corresponding set of decision support and analysis tools.

These areas are targeted for development.

- Structural Health Monitoring to reduce O&S cost and increase safety by incorporating maintenance feed back loop.
- Dynamic Systems Health Monitoring for robust analysis and detection algorithms can predict and assess the health of dynamic system components for Condition Based Maintenance, including fatigue critical metallic and composite structure and rotating assemblies. Component and system level risk and reliability assessment methods could also be developed.
- Avionics Systems Health Monitoring of onboard avionics systems.
- Integration of Health Monitoring Elements by collecting and managing IVHM data for engineering analysis, and integrating IVHM data with maintenance management systems and supply chain systems.
- Active Rotor Smoothing by automated data acquisition for Rotor Track & Balance (RTB) function. Real time automated in-flight RTB using blade trailing edge flaps and/or moving mass.
- Advanced Diagnostics and Prognostics Development to enable Condition Based Maintenance.
- In-flight, Real-Time Health Monitoring: Enabling technologies include sensor identification and development. Potential benefits are 1) Real time identification of incipient structural degradation; 2) Real time identification of systems degradation; 3) Increased safety; and 4) Improved mission performance.



## **System Health Operations Analysis Model**

The System Health Operational Analysis Model (SHOAM) was developed to support IVHM development by analyzing and demonstrating the operational impacts of IVHM solutions. The model creates systems with specific reliability characteristics, ages those systems by running them through realistic scenarios allowing failures to occur, and performing maintenance. The model runs two design solutions with varying levels of IVHM implementation and can incorporate multiple operational scenarios. Results from the SHOAM model include system operational availability and reliability comparisons and sensitivities. The following inputs are required:

- Operational Scenario
- Baseline Reliability and Maintainability Data
- Scheduled Maintenance
- IVHM Impacts

The SHOAM model was applied to analyze mission performance of a fleet of 25 CTR rotorcraft. Mean time between failures (MTBF) was based on data from the V-22 and the 777. Aircraft system repair times were based on the 737 NG, and rotorcraft system repair times were based on the CH-47D. Scheduled maintenance was based on the 737 NG. Three maintainers were assumed for each unscheduled maintenance action and 20 maintainers for scheduled checks. The subsystems were modeled equivalent to 2-digit Work Unit Code levels.

An average utilization of 6.5 flight hours per day was assumed, corresponding to 1,102 flights per aircraft per year, for a total of 27,542 fleet flights per year. SHOAM results indicated a 90.2% schedule reliability with an 88.6% operational availability, requiring only 1.7 maintenance man-hours per flight hour (MMH/FH). These are impressive numbers compared to typical military helicopter operations. In contrast, the MV-22 operational threshold targets are to be greater than 17 FH between aborts and less than 20 MMH/FH, with at least 82% operational readiness.

The CTR transport rotorcraft will operate point-to-point, thereby spending roughly 95% of its flight hours in cruise flight, at reduced rpm, reduced rotor thrust and loads, and at lower vibration levels than hover and conversion modes. Spending most of its flight time in the benign cruise flight environment should lower vibration induced maintenance to approach fixed wing levels. The lower disk loading rotor reduces hover power (for a given GW), contributing to reduced loads in the drive system.

Reduced cabin vibrations are considered essential to passenger acceptance. To the extent that passenger comfort levels are achieved, the low vibration environment will also reduce maintenance actions caused by vibration. So it is reasonable to expect civil transport rotorcraft will experience far fewer maintenance actions than their military counterparts.

## **Integrated Diagnostics**

The Integrated Diagnostics (ID) process is a structured process that maximizes the effectiveness of diagnostics by integrating pertinent elements, such as testability, automatic and manual testing, training, maintenance aiding, and technical information, as a means for providing a cost effective capability to detect and isolate unambiguously all faults known or expected to occur in aircraft systems and equipment in order to satisfy aircraft system mission requirements. The utilization of the SHOAM model and other business case tools will help optimize the mix of onboard and off-board diagnostics/prognostics elements within the CTR program. These highly structured integrated diagnostics systems engineering trade studies are performed at both a high level top-down approach at the beginning of the Concept of Operations phase and are continued interactively with a bottoms-up approach through out the design process to

ensure performance of all elements are optimized in the most affordable (e.g., size, cost, weight, reliability, mission, etc.) manner are taken into consideration.

Interacting with the Integrated Diagnostic process must be a highly structured, self-documenting diagnostic design process. This process consists of three basic steps:

- Functional Analysis with a focus on functional interdependency.
- Failure Mode Analysis with a focus on failure propagation.
- Test Strategy Analysis with a focus on points of observability for detection, isolation, or incipency.

Many legacy aircraft programs have typically failed to employ the above process with any degree of discipline, but rather placing high expectations on cutting edge technology solutions alone. Unfortunately, there are no substitutions for doing the methodical bottoms-up hard work in designing an effective diagnostic system. Boeing has taken many initiatives to align it more effectively to meet the needs of these challenges.

## **10. Net Benefits of the Advanced Technologies**

Many metrics can be viable measures of the benefits of advanced technologies. This study has focused on Cash DOC/ASM as a primary metric for aircraft systems analysis of operating cost. That is directly comparable to the Revenue/ASM of potential operators of civil transport rotorcraft. Other significant metrics may be empty weight (a primary influence on production costs), relative development costs (investment), relative production cost (acquisition), and Life Cycle Cost (LCC).

LCC includes development costs, production costs, operating cost (of the aircraft), and disposal cost; a difficult metric to estimate and one that few stake holders would care about. The aircraft manufacturer cares about the investment cost and production cost because they determine the cost-to-market and therefore the aircraft competitiveness. The aircraft operator cares about the balance between the revenue stream and the acquisition plus operating cost. As previously pointed out, the direct operating cost (fuel, oil, and maintenance) represent 63% of the rotorcrafts overall cost over a 30 year period.

### **10.1. Civil Tiltrotor**

#### **10.1.1. Advanced Technology Weight Benefits Applied To CTR**

A summary of weight benefits attributable to advanced technologies is shown in Table 26. The source of these benefits was identified in Section 9. A guide for the potential empty weight reduction is the product of each component's fraction of empty weight times its estimated weight reduction from advanced technologies. Examination of Table 26 shows the fuselage has far more potential to reduce empty weight than other structural components, but the drive system has the most overall potential. But that assertion assumes all advanced technologies have the same probability of reaching maturity, which is highly unlikely.

The likelihood of receiving adequate funding times the risk of reaching the stated goals at technical maturity are both unknowns, and should be given due consideration when NASA deliberates the distribution of funds to mature any of these advanced technologies.

Boeing must frequently decide where to invest development dollars to maximize the benefit during aircraft detail design. Certainly there is a clear answer if that choice is between a Key Performance Parameter (KPP) deliverable versus weight savings on a secondary component. But the choices are often not so clear. Consider for example, the tradeoff between weight savings from an expensive structural optimization versus redesigning the empennage configuration, which may benefit both weight and performance. That kind of dilemma is most often evaluated on the basis of dollars invested per net pound of empty weight saved (\$/lb). And it is very unlikely that the whole vehicle can be resized during detail design, so the weight savings are not amplified by a growth factor like those shown in this study's resizing exercise. The pound of weight saved may eventually be allocated to some other area of the rotorcraft to compensate an unexpected weight increase during detail design.

The net benefit of the individual structural weight reductions of Table 26 (excluding the rotor system) was evaluated by resizing the CTR for each component. The results on aircraft empty weight (EW) are shown in Figure 76.

**Table 26. Summary of Weight Benefits on CTR From Advanced Technology**

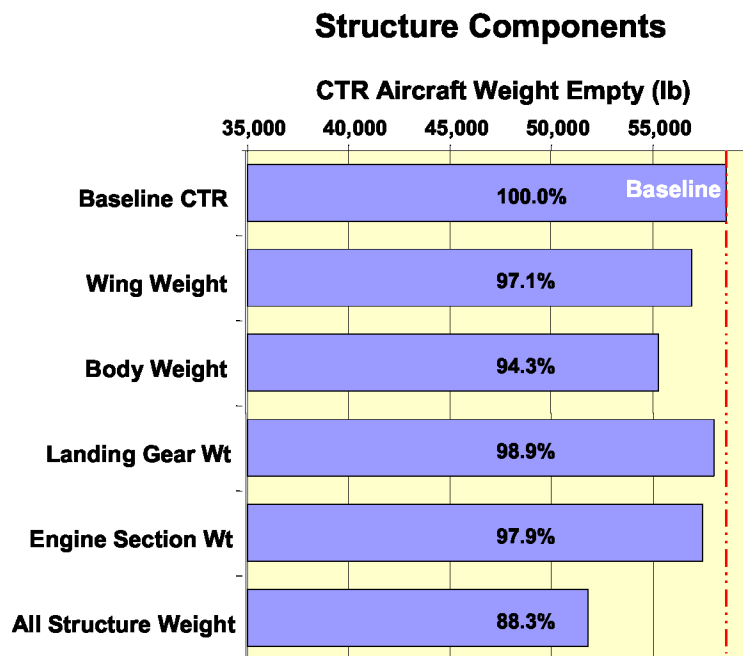
<b>Aircraft Component</b>	<b>% of Baseline Empty Weight</b>	<b>Potential Weight Reduction</b>
Advanced engine HP/wt ratio	5.9 %	35.0 %*
Advanced Structural materials and designs	[50.8 %]	
Wing	12.3 %	13.9 %
Fuselage	13.9 %	22.7 %
Empennage	1.5 %	18.7 %
Lighting Gear	2.4 %	22.1 %
Engine Section	5.5 %	18.7 %
Rotor – blades	7.6 %	15.0 %
Rotor – hub	6.5 %	6.8 %
Advanced Drive System	[13.6 %]	
Main rotor transmission		12.0 %
Advanced components		4.0 %
Advanced materials & processing		6.0 %
Investment development		8.0 %
Advanced flight controls	[6.2 %]	
Cockpit controls	0.3 %	9.0 %
Rotor upper controls	2.7 %	13.2 %
Fixed wing controls	2.4 %	17.2 %
Tilt mechanism	0.8%	12.5 %
Advanced Fixed equipment (Electrical, hydraulic, ECS, ice-protection, APU)	21.3 %	7.2 %

\* 60 % increase in engine HP/wt

### Advanced Structures Technology For CTR

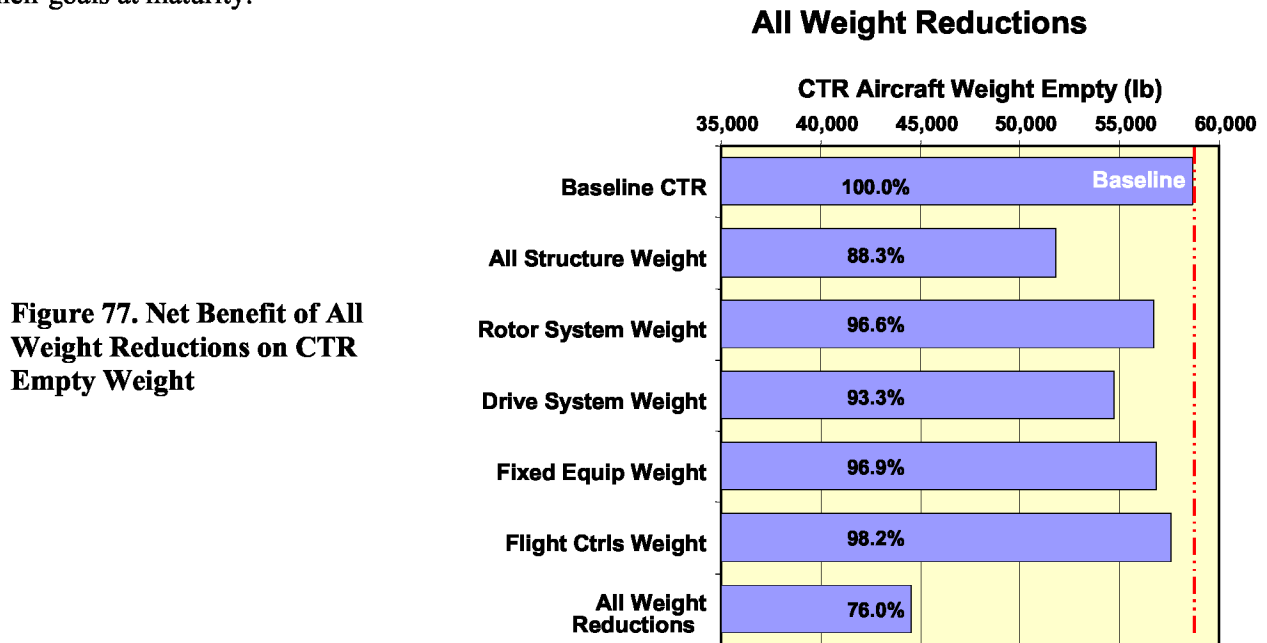
The effect of structural weight reductions on CTR weight empty is shown in Figure 76. Taken together, these advanced technologies have the potential to reduce rotorcraft empty weight by 11.7%. As expected, the fuselage weight reduction had the greatest individual impact, yielding a 5.7 % decrease in rotorcraft empty weight.

**Figure 76. Net Benefit of Structural Weight Reductions on CTR Empty Weight**



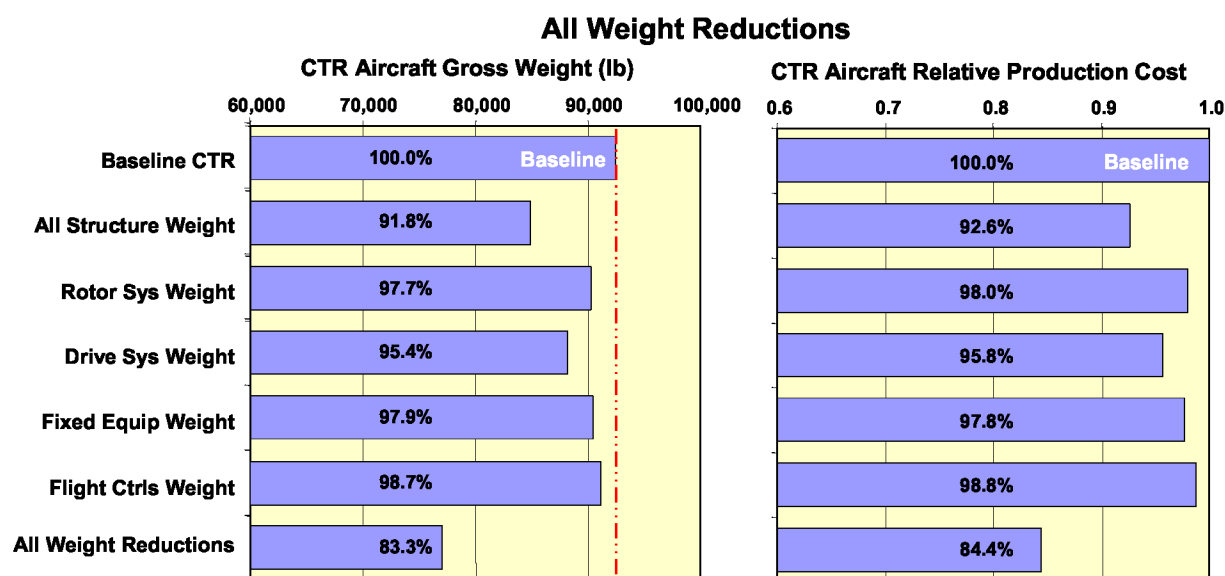
## All Advanced Technology For CTR Weight Reduction

Weight reductions also came from the engine, rotor system, flight controls, and fixed equipment. Figure 77 shows the effect of those weight reductions (and weight reductions from structures technology). The structures technology offered more benefit than the other areas. When all technologies were taken together, the down-sized aircraft had a net 24 % reduction in EW. The 7% EW reduction from the drive system stands out as next most attractive area for investment, given near equal probabilities of reaching their goals at maturity.

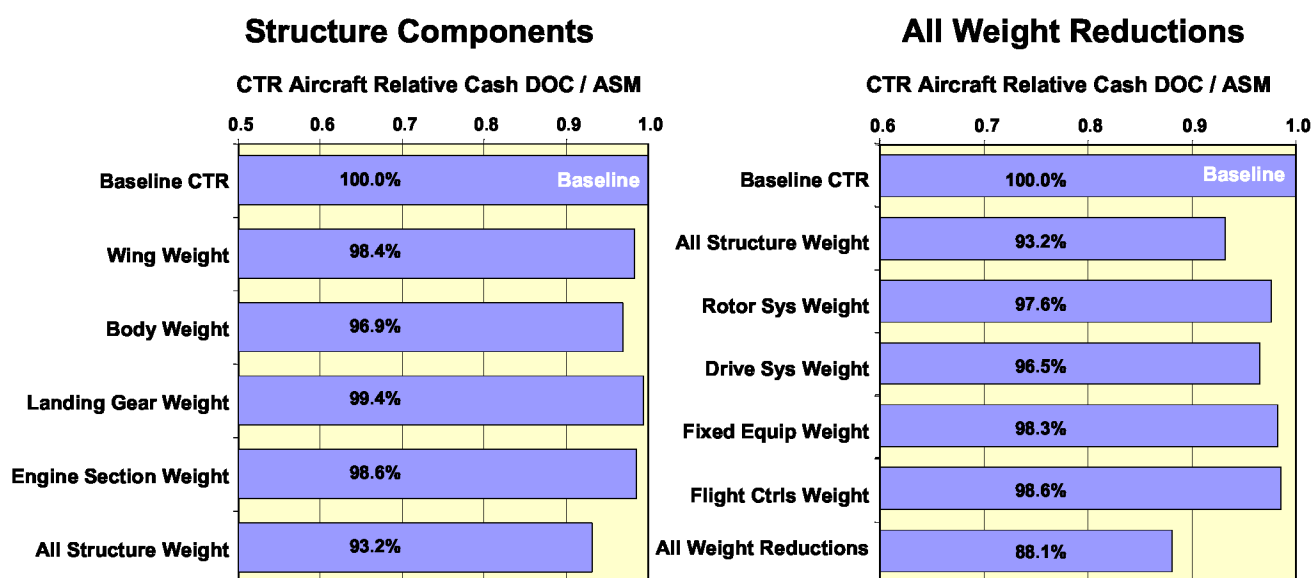


An EW reduction is usually considered a good indicator of production costs. The net benefit of all weight reductions on aircraft Gross Weight (GW) and production cost, shown in Figure 78, are similar to the benefit on EW. And the percentage benefits on production cost were nearly the same as those on GW.

Weight reductions also benefit Cash DOC/ASM operating cost. The fuselage size doesn't change size, it is fixed to accommodate the 100 passengers. But the wing and rotor both decrease in size as GW decreases (for constant wing loading and disk loading). The wing cruise CL may change very little with size for a fixed wing loading, but smaller areas for the wing, nacelle, and empennage do reduce profile drag and therefore reduce the amount of required fuel. Just as adding a pound of weight to the aircraft EW gets compounded into 2.5 to 3.0 more pounds GW due to the growth factor, subtracting a pound decreases the GW similarly. The benefit of reduced weight on CTR Cash DOC/ASM is shown in Figure 79.



**Figure 78. Net Benefit of All Weight Reductions on CTR Gross Weight and Production Cost**



**Figure 79. Net Benefit of All Weight Reductions on CTR Cash DOC/ASM**

### 10.1.2. Advanced Propulsion Benefits Applied To CTR

Section 8.1 described several advanced engine technology programs. A “best guess” for the SFC of an advanced technology production engine was a 20.5% reduction in SFC, relative to the standard AE1107C, by the 2020 time frame. This was applied to both the SMRC and CTR evaluations, with the appropriate SFC for the engine size of the each rotorcraft.

Table 27 summarizes the result when the CTR was resized with the 20.5% reduction in SFC. Relative DOC/ASM showed the most benefit with a 16% reduction, as it is most sensitive to fuel burn. The resized CTR with the advanced engine burned 23% less fuel than the baseline CTR.

A 60% increase in HP/weight of the advanced engine was added to the improved SFC, shown in the right hand column. The reduced engine weight did little to reduce the fuel burn, only reducing it by the down-sizing of the CTR, but it greatly benefited the CTR empty weight and therefore the gross weight. Reduced engine weight also reduces the engine section weight (under structures) and the engine systems weight, which amplifies the benefit.

**Table 27. Effect of Advanced Engine Technology on CTR**

<b>Attribute</b>	<b>Baseline CTR</b>	<b>Resized CTR Adv SFC</b>	<b>Resized CTR Adv SFC+Eng Wt.</b>
Gross Weight	92450	88580	83525
Empty Weight	58646	57103	52411
Weight of Fuel	10087	7761	7400
Relative Production Cost	100 %	98 %	98 %
Relative DOC/ASM	100 %	84 %	84 %

### **10.1.3. Advanced Performance Technology Applied To CTR**

Performance improvements from advanced technologies were applied cumulatively. The basic parasite drag reduction was applied first, followed by advanced technologies for reduced wing thickness, the advanced passive CTR rotor, and then reduced hover download. The cruise altitude of 24,000 ft and airspeed of 305 ktas were kept constant as the new technologies were applied. A brief description of each basic improvement follows.

Overall, the CTR parasite drag (fe) was reduced by 23%, from 30.1 sq.ft. down to 23.4 sq.ft. for the baseline CTR. Resizing the aircraft with the new fe gave a small further reduction due to wing and empennage down-sizing. The technology basis for this was discussed in section 9.3.6. Further justification could be made by applying AFC in cruise to maintain attached flow throughout cruise.

The baseline CTR wing was 23% thick, based on the V-22. It was reduced to 20% as an advanced design improvement, which reduced the wing Cdo and compressibility drag, but increased the wing weight. Compressibility drag was reduced by shifting the Mach number tables 0.01 Mach for each 1% reduction in the wing t/c, so reducing wing t/c from 0.23 to 0.20 gave a 0.03 increase in the Mach number tables for compressible drag. The wing was subsequently evaluated at a 18% thickness, in the same manner.

The advanced CTR rotor improved cruise efficiency by 5% at 300 ktas and by nearly 13% at 350 ktas, as presented in section 8.6.3. The advanced CTR rotor cruise efficiency was calculated to be 0.845 at 305 ktas and 0.840 at 350 ktas. Hover efficiency changed very little from the baseline rotor to the advanced rotor (0.738 FM versus 0.75 FM).

A 24% reduction in hover download was assumed from the application of AFC, as discussed in section 8.7.1

Table 28 is a tabulation of the results from successive introduction of advanced performance technologies. The equivalent flat plate area is shown for each combination, as it was affected both by scaling with the aircraft total wetted area and by the different wing thickness ratios.

**Table 28. Advanced Performance Technology Benefits To The CTR**

<b>Configuration</b>	<b>Gross Weight</b>	<b>Weight of Fuel</b>	<b>Empty Weight</b>	<b>Relative Production Cost</b>	<b>Relative DOC/ASM</b>
Baseline CTR (fe=30)	92450	10087	58646	1.0000	1.0000
Reduced Parasite Drag (fe=22.6)	90165	9022	57426	0.974	0.924
Reduced fe with 0.20 Wing t/c (fe=21.2)	89995	8624	57656	0.975	0.898
Reduced fe + Advanced Rotor (fe=22.4)	89188	8706	56766	0.962	0.900
Reduced fe with 0.18 Wing t/c + Advanced Rotor + Reduced Download (fe=20.15)	88583	7966	56901	0.959	0.852
Reduced fe with 0.18 Wing t/c + Advanced Rotor + Reduced Download + Advanced Engine SFC (fe=19.6)	85075	6075	55284	0.935	0.722

## 10.2. Single Main Rotor Compound Helicopter

A summary of SMRC weight benefits attributable to advanced technologies is shown in Table 29. The source of these benefits was identified in Section 9. Most weight benefits are the same as those of the CTR. The structural benefits were assessed differently for the two concepts, resulting in a larger wing weight reduction for the SMRC. That may be a feasible outcome since the SMRC wing is not designed to be picked up by the wing tips as a tilt rotor configuration must be, nor is it subject to the structural dynamics requirements of a tilt rotor, such as whirl flutter.

Other differences between the CTR and the SMRC of Table 29 are the addition of the auxiliary propellers and auxiliary drive for the SMRC propellers, and the absence of a tilt mechanism.



**Table 29. Summary of Weight Benefits on SMRC From Advanced Technology**

<b>Aircraft Component</b>	<b>% of Baseline Empty Weight</b>	<b>Potential Weight Reduction</b>
Advanced engine HP/wt ratio	5.8 %	35.0 % *
Advanced Structural materials and designs	[39.5 %]	
Wing	14.8 %	8.0 %
Fuselage	17.3 %	13.0%
Empennage	1.7 %	18.7 %
Lighting Gear	5.3 %	22.1 %
Engine Section	0.5 %	18.7 %
Rotor – blades	7.9 %	15.0 %
Rotor – hub	4.8 %	6.8 %
Auxiliary Propellers	1.7 %	
Advanced Drive System	[14.8 %]	
Primary drive system		22.0 %
Auxiliary drive system		30.0 %
Advanced flight controls	[4.6 %]	
Cockpit controls	0.3 %	9.0 %
Rotor upper controls & systems controls	3.4 %	-13.2 %
Fixed wing controls & aux flight controls	0.8 %	-17.2 %
Tilt mechanism	NA	NA
Advanced Fixed equipment (Electrical, etc)	18.2 %	- 7.2 %

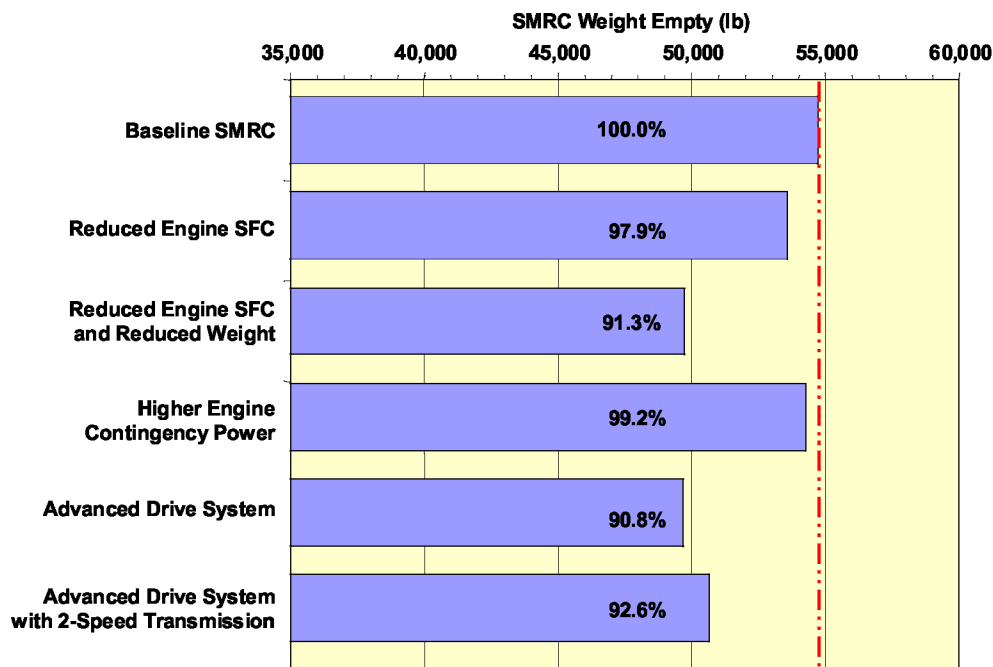
\* 60 % increase in engine HP/wt

### **10.2.1. Advanced Engine and Drive System Technology For SMRC**

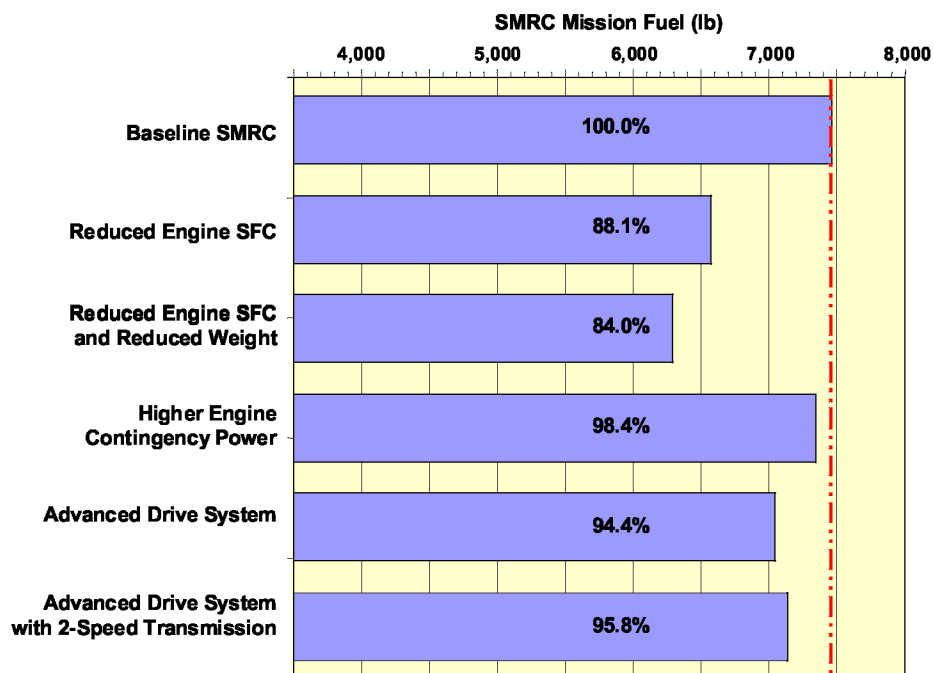
Advanced engine technology was found to have more potential benefit than other individual technologies for the SMRC helicopter, and for the CTR. Section 8.1 described several advanced engine technology programs. An advanced technology production engine was modeled with a 20.5% reduction in SFC, relative to the standard AE1107C. The advanced engine SFC from the “best guess” curve of Figure 71 for the SMRC baseline engine power of 4940 SHP per engine gave 0.33 lb/hr/SHP for the advanced engine at max takeoff rating. A 12% reduction in fuel flow was required to adjust the baseline engine model to the advanced SFC.

The benefits of reduced SFC and the combined benefit of reduced SFC with increased HP/weight to SMRC empty weight are shown in Figure 80. As previously discussed, reduced engine weight directly effects empty weight, compounded by the associated weight of engine systems and the structural engine section. Reduced SFC has more effect on mission fuel, as shown in Figure 81, with an indirect reduction in Gross weight (not shown). Higher engine contingency power does little to either empty weight or mission fuel. The assumed increase in contingency power may come with an increase in engine weight, but this was an unknown effect and was not modeled. So the increase in contingency power allowed a slightly smaller “installed” power with a slight improvement in cruise fuel flow.

**Figure 80.**  
Advanced Engine  
and Drive System  
Technology  
Benefits to  
SMRC Empty  
Weight



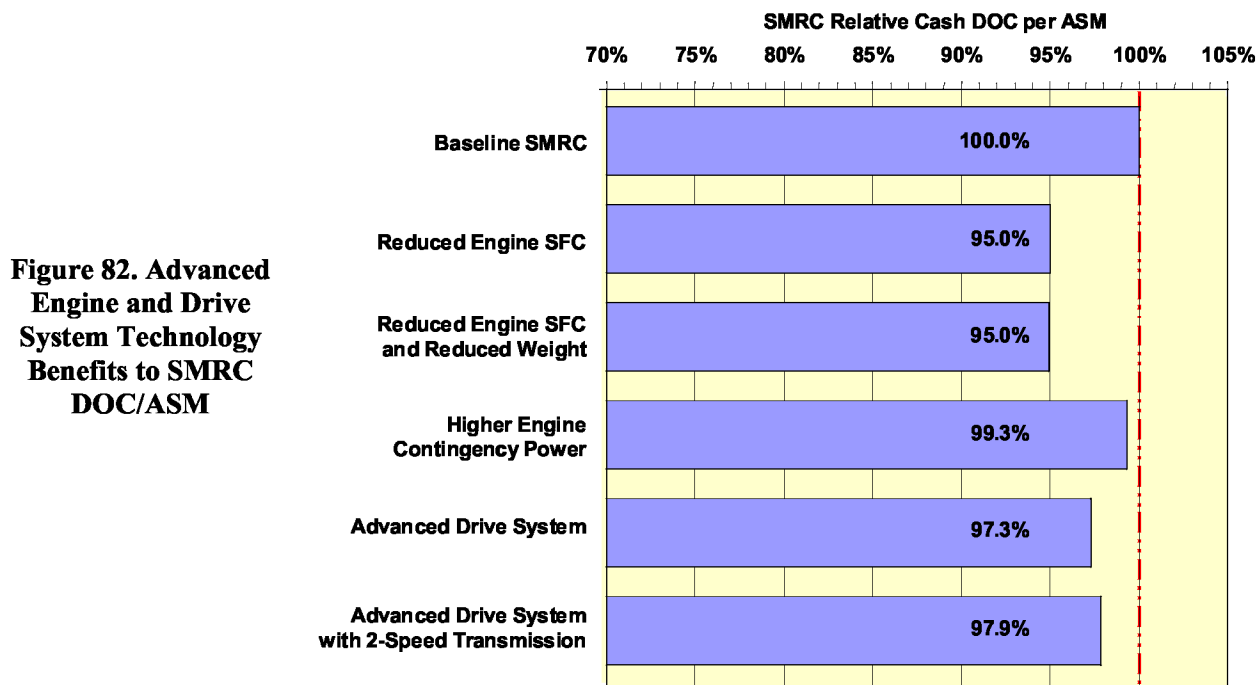
**Figure 81.**  
Advanced Engine  
and Drive System  
Technology Benefits  
to SMRC Mission  
Fuel



Figures 81 and 82 also show the benefit of reduced weight from advanced drive system technologies (as a group), and the slight weight increase associated with the introduction of a 2-speed gearbox for reduced rotor rpm in cruise. Somewhat surprisingly, the potential empty weight reductions from advanced drive systems are nearly equal to the advanced engine technology, but only offer secondary reductions in mission fuel, about ½ of the net benefit from advanced engines.

The net benefit of advanced engines and advanced drive systems on relative DOC/ASM are shown in Figure 82, where 100% was the baseline SMRC DOC/ASM. Reduced fuel consumption from advanced

engine technology gave a 5% reduction in DOC/ASM. In contrast, weight reductions from the advanced drive system, indirectly reduced fuel and therefore reduced DOC/ASM by only 2.5%.



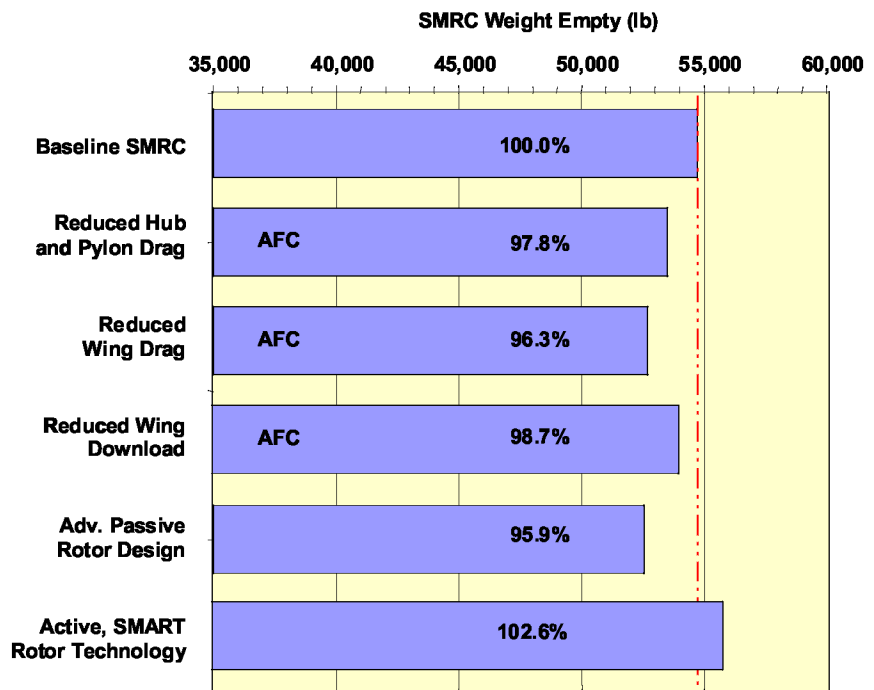
### 10.2.2. Advanced Performance Technology Applied To SMRC

This section examines the benefit of several technologies for advanced performance, including reduced hub drag, wing drag, wing download in hover, an improved passive blade design, and application of the SMART rotor concept. As shown in Figure 83, the advanced AFC technology accounted for both the drag reduction and the download reduction. Performance benefits do not generally show much benefit to empty weight, as evidenced here. The empty weight reductions to the SMRC from these performance improvements were between 1.3% and 4.1%.

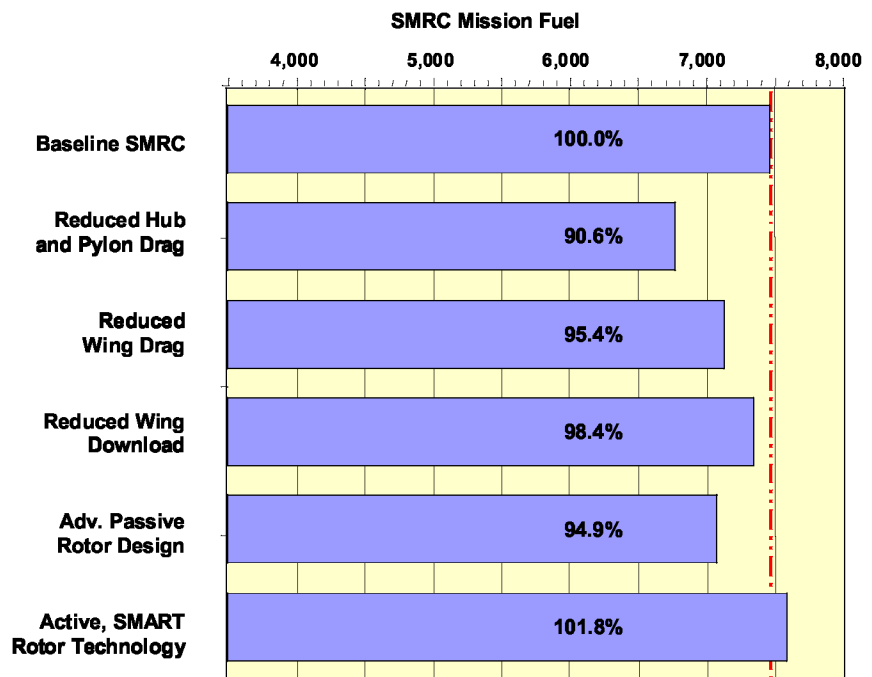
The active SMART rotor concept does not fare well when compared on a weight basis. Its strength is in noise reduction and vibration reduction, and both have been acknowledged as key elements to the success of any civil transport rotorcraft. A fair comparison would be against other means of achieving noise or vibration reduction, on a \$/lb basis.

Improved performance from advanced technologies is very effective at reducing mission fuel, as shown in Figure 84. Mission fuel was reduced between 5% and 9.4% by the individual technologies. When taken together, the combination of drag reduction, reduced download, and the advanced passive blade design yield the potential for a 19% reduction in mission fuel.

**Figure 83. Advanced Performance Technology Benefits To SMRC Empty Weight**



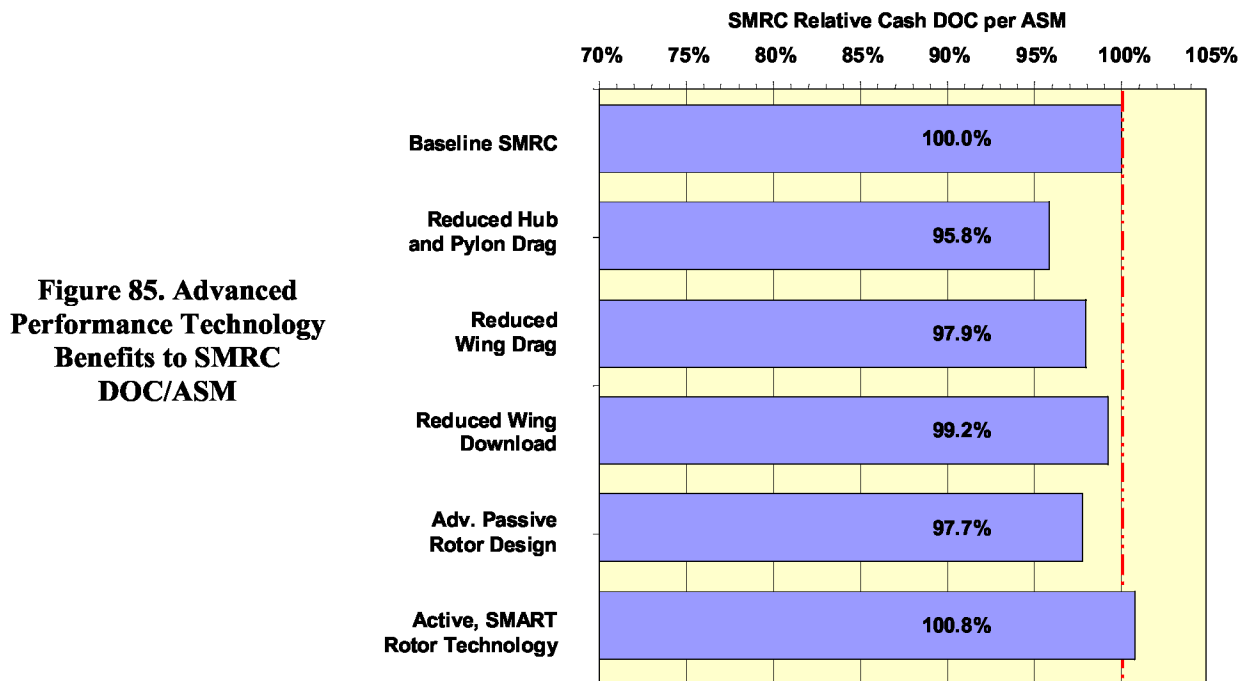
**Figure 84. Advanced Performance Technology Benefits to SMRC Mission Fuel**



The net benefit of this group on DOC/ASM is shown in Figure 85. The DOC/ASM values reflect a combination of reduced fuel cost and reduced maintenance cost (from the reduced empty weight), and are easily understood. Referring back to Figure 16 and removing the cost of financing and depreciation that are not part of DOC/ASM, fuel and oil represent about 44% of DOC/ASM and maintenance represents about 28%. Then the net benefit of reduced hub and pylon drag on mission fuel would yield  $(1 - 0.906) \times 0.44$ , or a 4% reduction in the fuel cost portion of DOC/ASM. And the benefit of that technology

on empty weight would be  $(1-0.978)*0.28$ , or approximately a 0.6% reduction in the maintenance cost portion of DOC/ASM. The total of 4.6% is close to the actual reduction of 4.2% from Figure 85.

These advanced performance technologies gave a net benefit of between 0.8% and 4.2% reduction in DOC/ASM, excluding the SMART rotor technology. And taken together they may provide a 9.1% reduction in DOC/ASM.



### 10.2.3. Advanced Technology For SMRC Weight Reduction and For All Technologies

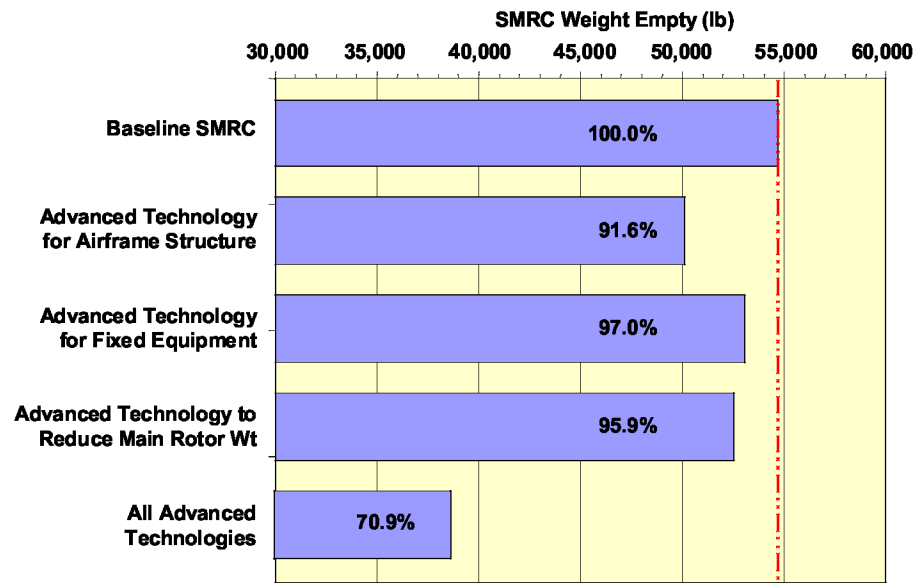
The net benefits of the individual structural weight reductions of Table 30 (excluding the drive system) were evaluated by resizing the SMRC for each major group in the table. The results on aircraft empty weight, mission fuel, and DOC/ASM are shown in Figure 86, Figure 87, and Figure 88, respectively. Advanced technology applied to the airframe structure (wing and body) was more effective than weight reductions in fixed equipment or in rotor system weight, in all three metrics. But together they would reduce SMRC empty weight by approximately 15% (based on the products of their individual benefits), a substantial benefit. In fact, it is half of the 29% net benefit from all the advanced technologies applied to the SMRC, as shown by the bottom bar.

Advanced technology that reduced structure weight, fixed equipment weight and main rotor weight yielded between 2% and 5% reductions in mission fuel. But all advanced technologies reduced the SMRC mission fuel by an outstanding 39%. Obviously, the compounding effects of technology on technology are both real and important, i.e. they are multiplicative, not additive.

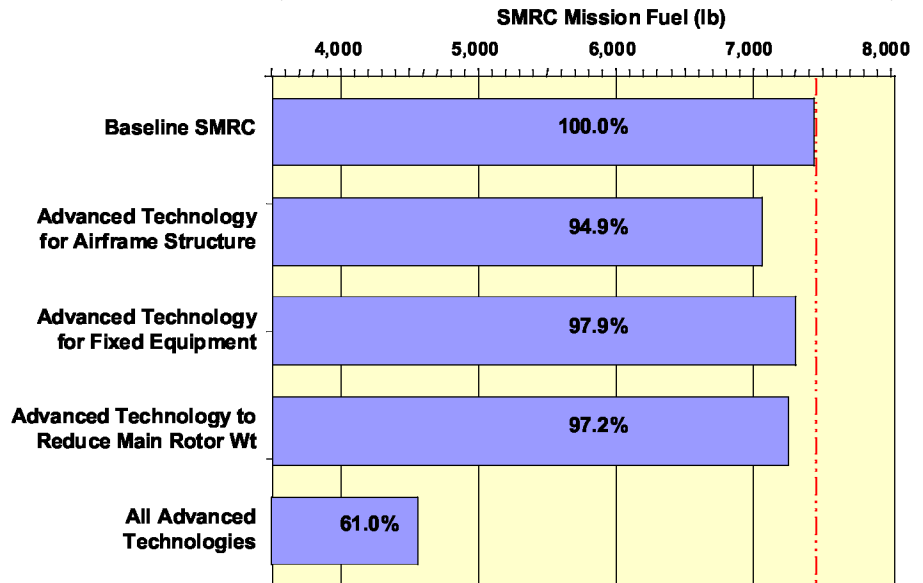
DOC/ASM is primarily a reflection of mission fuel for a fixed cruise airspeed, as previously shown. So weight reductions from this group resulted in very small benefits to DOC/ASM, between 1% and 2.5%. But the net benefit of all technologies produced a 17% reduction in DOC/ASM. Most airlines today would be ecstatic with only a quarter of that reduction in their operating costs.

More detailed charts of advanced technology benefits on the SMRC are in Appendix C.

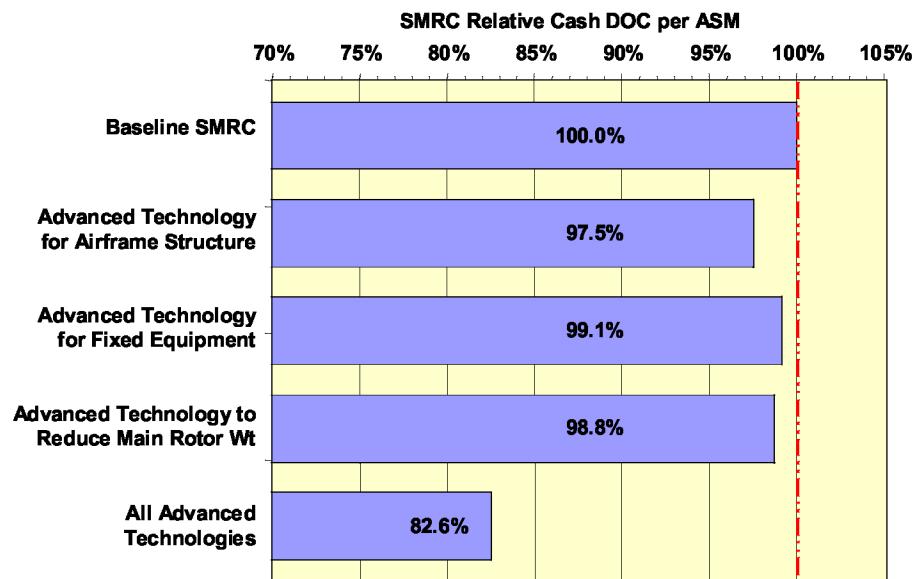
**Figure 86. Advanced Structures Technology Benefits To SMRC Empty Weight**



**Figure 87. Advanced Structures Technology Benefits To SMRC Mission Fuel**



**Figure 88. Advanced Structures Technology Benefits To SMRC DOC/ASM**



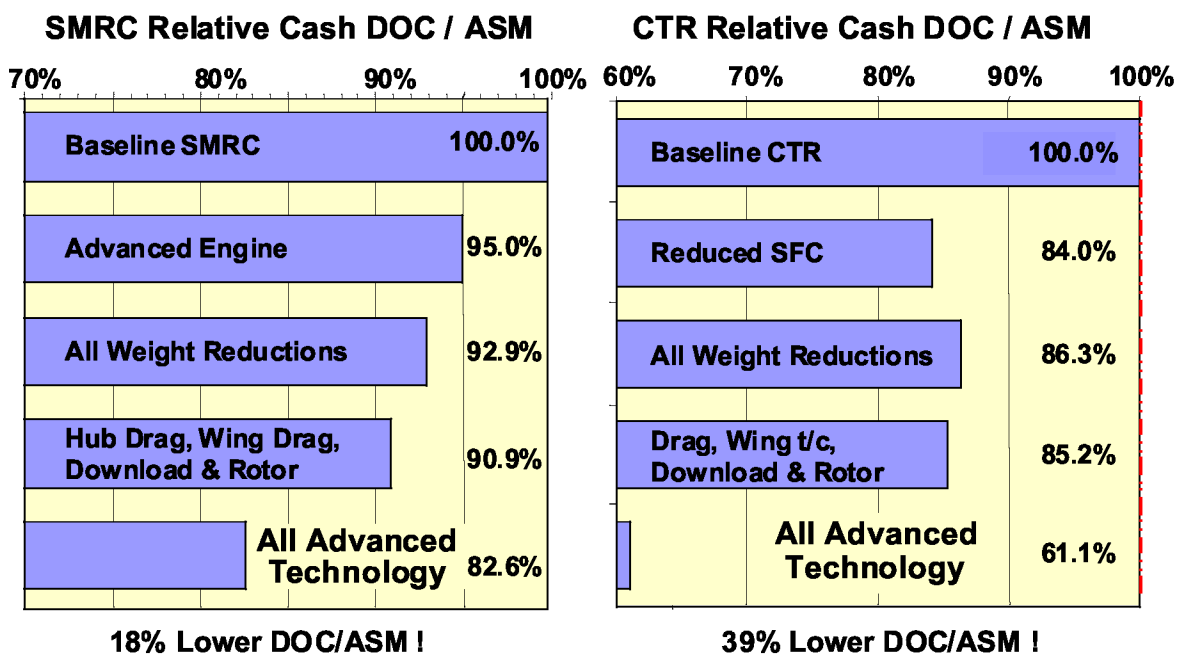
### 10.3. Combined Benefits Of Advanced Technologies

Application of all the selected advanced technologies results in enormous reductions of vehicle size, installed horsepower, and mission fuel, see Table 30. The CTR mission fuel with all advanced technologies was reduced to 50% of the original baseline design, and the SMRC mission fuel was reduced by 40%.

**Table 30. Combined Benefit of All Advanced Technology To CTR and SMRC**

<u>Civil Tilt Rotor</u>			<u>SMRC</u>		
	<u>Baseline</u>	<u>All Adv. Tech.</u>		<u>Baseline</u>	<u>All Adv. Tech.</u>
Wing span	72.5 ft	64.4 ft	Wing span	97.5 ft	83.4 ft
Rotor dia.	60.6 ft	52.6 ft	Rotor dia.	82.5 ft	71.2 ft
Installed SHP	23,300	15,800	Installed SHP	19,760	12,520
Empty weight	58,600 lbs	40,600 lbs	Empty weight	54,700 lbs	37,180 lbs
Mission Fuel	10,100 lbs	5,100 lbs	Mission Fuel	7,460 lbs	4,500 lbs
Gross weight	92,400 lbs	69,400 lbs	Gross weight	80,170 lbs	59,690 lbs
%Avg Unit Prod	100 %	67.5 %	%Avg Unit Prod	100 %	75.1 %
Cash DOC/ASM	\$ 0.194	\$ 0.119	Cash DOC/ASM	\$ 0.421	\$ 0.341

A side-by-side comparison of advanced technologies to the SMRC and the CTR are shown in Figure 89. The CTR showed more benefit from advanced technologies in all categories, even though the percentage improvements of individual technologies were fairly similar. This difference may be due in part to the longer design range of the CTR. (600 nm versus 350 nm for the SMRC), which required a 16% higher ratio of fuel/gross weight.



**Figure 89. Benefit Of All Advanced Technologies To SMRC and CTR DOC/ASM**



## 11. Acoustic Enablers

### 11.1. Terminal Area Noise

"Terminal area noise requirements" are not mandated by government agencies. They are usually instituted through local city ordinances or through voluntary noise restrictions to quell neighborhood complaints about noise in the vicinity of airports/heliports.

There are, however, civil aviation regulations limiting rotorcraft noise during specifically defined flight operations. All civil aircraft must comply with the specified limits, which are a function of maximum takeoff gross weight. These flight operations are typically defined by worst-case flyover noise scenarios. For example, civil noise regulation compliance testing requires tilt rotors to takeoff in helicopter mode only. This operation requires maximum rotor speed with a nacelle angle that produces the best rate-of-climb ( $V_Y$ ). Although a tilt rotor can fully transition to forward flight mode within about 10 seconds, this transition is not permitted during any portion of the takeoff noise compliance test. Therefore, civil certification noise measurements are not representative of the potential for quiet terminal area operations.

The same holds true for helicopters. Although pilots typically approach-to-land using a decelerating airspeed at 3° glide slope, the civil certification noise compliance testing requires a noisier 6° glide slope at a constant  $V_Y$  airspeed.

One method for minimizing noise in the vicinity of terminal areas is to institute a "fly-neighborly" program like that proposed by the Helicopter Association International (HAI), which encourages pilots to use noise abatement flight operations around terminal areas. These operations could include flight routes that are limited to areas that minimize noise exposure to surrounding communities, and/or active management of airspeed and power settings to reduce source noise levels.

External noise for any rotorcraft is driven largely by rotor tip speed. Because tilt rotors are less efficient as lifting rotors, they require significantly higher tip speeds than those of conventional helicopters during liftoff. However, if the tilt rotor can quickly transition to forward flight mode with nacelles at or near the 0° position, source noise can be reduced significantly, effectively reducing the takeoff noise footprint, to much lower levels than that of an equivalent helicopter.

Noise "exposure" to a given area is a generally a function of source levels, duration of exposure, and the number of noise events per 24-hour period (i.e., takeoffs and landings). Terminal area noise limits can be established using any of several noise metrics, including:

SEL	Sound Exposure Level, dBA
EPNL	Effective perceived noise level, EPNdB
$\text{dBA}_{\text{max}}$	maximum A-weighted noise level, dBA
$L_{\text{DN}}$	Day-Night Average noise level, dBA

The A-weighted scale (dBA) is a simplified filtering network that is based on the equal loudness contours for human hearing response. It has become an internationally standardized weighting curve that is easily implemented in the most basic sound level meters. EPNL is the most comprehensive metric used by civil aviation authorities for aircraft noise certification compliance testing. It is a time-integrated noise metric that captures the noise generated during a flyover event. For rotorcraft, there are published values for each of the three flight conditions that are tested – level flyovers, takeoffs, and approach descents. SEL is a simpler time-integrated noise metric that is also used by civil aviation authorities, but is currently restricted to rotorcraft with maximum gross weights of 7000 lbs or less. The  $\text{dBA}_{\text{max}}$  value is

easily measured for transient flyover events. It captures the maximum A-weighted noise level generated during a flyover event, and can be implemented at terminal area boundaries for monitoring and enforcement of fly-neighborly programs or municipal noise restrictions. The  $L_{DN}$  value is a time-averaged noise level for measuring the cumulative noise exposure from all aircraft operating in a terminal area over the course of a 24-hour day. Night time operations between the hours of 7 pm and 7 am are "penalized" by adding 10 dBA to the noise values generated during that time. The use of SEL and EPNL values generated from noise certification tests do not account for the potential noise reductions achieved from noise abatement flight operations.

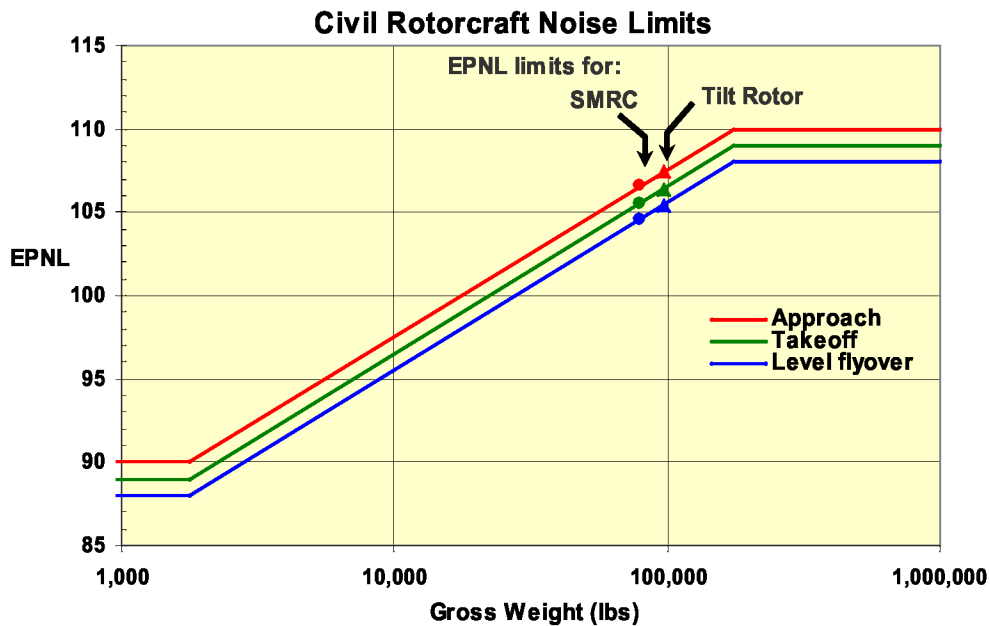
## 11.2. Noise Regulation Compliance

The noise limits imposed on helicopters and tilt rotor aircraft are a function of gross weight, and are currently identical for both types. As of this date, noise certification flight test procedures do not formally exist for tilt rotor aircraft. However, guidelines have been developed for the noise certification of tilt-rotor aircraft, and are presented in Attachment F of ICAO *Annex 16 — Environmental Protection, Volume I — Aircraft Noise*. They were developed specifically for the noise certification of the Bell/Agusta 609, the first example of a civil tilt-rotor aircraft. It is also intended that these guidelines be used as the basis for noise certification of subsequent tilt rotor aircraft.

Demonstration of compliance requires flyover noise measurements along the flight path and on either side of the aircraft during level flight, takeoff climb, and approach descent. Because the noise compliance testing requirements are generally based on worst-case noise conditions, the compliance margins for takeoff are likely to favor conventional helicopters over tilt rotors (with the exception of level flight). For compound helicopters, a similar regulation has yet to be developed, but the compliance demonstration testing would likely be similar to the existing rules in that, regardless of the propulsion options, it would probably have to operate just like a helicopter during takeoff and landing. Although the single main rotor compound (SMRC) Baseline Design has a low-noise main rotor due to its low tip speed (650 ft/sec), the high tip-speed (900 ft/sec) propellers would add significant risk to noise regulation compliance. The Civil Tilt Rotor hover tip speed (750 ft/sec) is significantly less than the V-22 hover tip speed (820 ft/sec). The V-22 does comply with current noise limits, which suggests a low risk of non-compliance for the large civil transport variant.

The noise certification limits, as defined by the FAA, are plotted below. The metric is the time-integrated Effective Perceived Noise Level (EPNL). Note that the limits for the SMRC and Tilt Rotor Baseline designs are indicated on the curves.

Of the three noise certification flight conditions specified, takeoff climb is the only one that is performance dependent. So for aircraft that have good climb performance, there is a potential for lower noise levels during this operation due to the ability to pull away from the ground-based microphones more quickly. This also has the effect of minimizing the takeoff noise exposure "footprint" area on the ground. Calculated maximum rate of climb (ROC), at takeoff atmospheric conditions, is 4230 ft/min for the SMRC Baseline Design and 3010 ft/min for the civil tilt rotor (CTR) baseline design. Maximum ROC for a typical helicopter, such as the EH101, is 1998 fpm, while MROC for the V-22 is 2320 fpm. The baseline designs for both the SMRC and CTR offer maximum rates-of-climb that are significantly higher than current state-of-the-art rotorcraft, and therefore have greater potential for large noise certification compliance margins, as well as relatively smaller noise footprints.



**Figure 90. Civil Rotorcraft Noise Limits**

For helicopters, the level flyover airspeed is defined as  $0.9V_H$ , and the airspeed for both takeoff and approach is  $V_Y$  (best rate-of-climb speed). The guidelines for tilt rotors specify that level flyovers be conducted in both airplane mode and helicopter mode. For airplane mode, two conditions are measured:

- with the high RPM and the same speed as used in the helicopter mode flyover.
- with the cruise RPM and speed  $V_{mcp}$ , which is intended to represent a worst case cruise condition.

For helicopter mode, there will normally be a nacelle angle below which hover is no longer possible and for which flight with zero airspeed is not permitted. The nacelle angle is fixed to the "gate" closest to that angle. [Note: In the design of the Bell/Agusta 609, there are a number of preferred nacelle angle positions called "gates". These are default positions that will normally be used for normal operation of the aircraft. The "gate" concept is expected to be typical for all future tilt rotors, although the number and position of the gates may vary.]

For the approach reference configuration, the nacelle angle for maximum approach noise is used. This is in line with the noise certification philosophy that requires the noisiest configuration for approach. This will normally require testing tilt rotors at several different nacelle angles in order to determine which is noisiest.

In the tilt rotor aircraft design, the wing flap angle varies with airspeed, so the pilot may manually set flaps or may use auto-flap control in order to reduce the pilot's workload. In this latter case, the flap angle for noise certification will be the flap angle that is normal for the approach configuration and approach condition flown. For a design with pilot-controlled flap angle, the applicant should use the flap angle designated for approach and will have to prove that the noisiest configuration is used for noise certification.

### 11.2.1. Single Main Rotor Compound Helicopter (SMRC)

For the Baseline SMRC with a gross weight of 80,170 lbs, its certification noise limits are:

level flyover	104.6 EPNdB
takeoff climb	105.6 EPNdB
approach descent	106.6 EPNdB

For terminal area operations, the Baseline Design SMRC (without a multi-speed gearbox) would produce noise primarily from the wing-mounted propellers, which provide anti-torque and yaw control during hover and low-speed flight. While the main rotor has a relatively low tip speed of 650 ft/sec, the propellers could potentially be noisy with their high 900 ft/sec tip speed. The high tip speed propellers could increase the risk of failure to comply with noise limits imposed by civil aviation regulatory agencies.

For cruise operation, the Baseline Design engine/rotor/propeller system would be slowed to limit the rotor advancing blade tip Mach number ( $M_{AT}$ ). Although the main rotor RPM would be reduced, the higher airspeed would produce a relatively high  $M_{AT}$  of 0.81 at the design mission cruise airspeed and altitude of 250 KTAS and 20,000 ft ISA. However, the potentially high noise produced by the main rotor at this high altitude may not have a measurable effect on the ground. The propellers would have an in-plane tip speed of 756 ft/sec during the cruise condition, producing a helical tip Mach number of approximately 0.84. While propeller noise at cruise altitude would not likely have a significant impact on the ground, it might contribute to the cabin noise environment. However, the outboard placement of the propellers would help mitigate their potential for contributing to cabin noise.

Due to the direct coupling of the main rotor and propellers in the Baseline Design SMRC, by cross-shafting through the main rotor transmission, the rotor and propeller tip speeds cannot be independently optimized for low noise. However, with the application of a multi-speed transmission for the main rotor, the propellers can be designed for a significantly lower tip speed in hover and low speed flight, without the propeller tip speed being too low for the high speed cruise, where the main rotor must be slowed. This would significantly reduce propeller noise in certification flight test takeoff climb and approach decent, and in terminal area operations.

### 11.2.2. Civil Tilt Rotor (CTR)

For the Baseline design CTR, with a gross weight of 96,613 lbs, its certification noise limits are:

level flyover	105.4 EPNdB
takeoff climb	106.4 EPNdB
approach descent	107.4 EPNdB

The design is configured with 4-bladed rotors, versus the 3-bladed rotors currently used on the V-22 Osprey. The baseline CTR configuration hover tip speed is 750 ft/sec, lower than that of the V-22 (which has 820 ft/sec), but it is somewhat high compared to conventional helicopter rotors. It is, therefore, noisiest during vertical lift operations. However, its ability to transition rather quickly facilitates noise abatement operations for terminal area operations. In cruise mode, the rotors would operate in propeller mode at a reduced tip speed of 637.5 ft/sec, producing a helical tip Mach number of 0.79 at the design mission cruise airspeed and altitude of 305 KTAS and 24,000 ft ISA. Although this tip Mach number is lower than that of the Baseline Design SMRC propellers for the design cruise point, the closest point of the tip path is nearer to the fuselage, which makes it a contributing factor for cabin noise.

### 11.2.3. Goals for Civil Transport Noise Regulation Compliance

The EH101 medium-lift helicopter is possibly the largest helicopter that has been demonstrated to comply with civil rotorcraft noise regulations. This model provides a starting point for evaluating the noise of large transport rotorcraft. It is manufactured by Agusta-Westland International Ltd (formerly EH Industries). The EH101 was developed for both civil and military applications, and can carry up to 30 passengers. It has a five-blade main rotor with a hover tip speed of 670 fps, and a four-blade teetering tail rotor with a hover tip speed of 650 fps.



**Figure 91 Agusta-Westland EH101 Medium-Lift Helicopter**

Noise certification flight testing was completed for the EH101-310 and -510 variants in 1997. They have a gross takeoff weight of 32,187 lbs (14,600 kg) and have the following noise certification values expressed in Effective Perceived Noise Level (EPNL in EPNdB):

<b><u>Operation</u></b>	<b>Limit</b>	<b>Measured Value</b>	<b>Compliance Margin</b>
level flyover	100.6	93.6	7.0
takeoff climb	101.6	97.6	4.0
approach descent	102.6	99.5	3.1

These compliance margins are fairly consistent with those of the current fleet of civil helicopters, and typical of 1990s rotor technology. The EH101 can be used as a guide for establishing advanced civil transport design goals for noise regulation compliance.

The noisiest flight operation is approach descent, due to main rotor blade-vortex interaction (BVI), and helicopters typically have the lowest compliance margin for this condition. Advanced rotor technologies are likely to benefit this flight condition the most (see Section 4).

It would be reasonable to assume that for conventional helicopters, the main and tail rotors contribute almost equally to the noise produced during level flyover and takeoff, while the main rotor dominates during approach descent. Given the main rotor low tip speed of 650 fps for the Baseline Design SMRC during terminal area operations, the dominant noise source for takeoff, and possibly approach, would be

the high tip speed propellers. Therefore, with relatively low compliance margins already in place for existing transport helicopters during approach descent and takeoff climb, the high tip speed propellers underscore the risk of non-compliance, and the need for advanced design features such as a two-speed transmission to accommodate lower propeller tip speeds on the SMRC. As discussed in Section 2.0, the noise certification procedures for approach descent are generally defined for the noisiest flight configuration. Noise certification regulations require a fixed configuration during approach (i.e. fixed flap settings, rpm, glide slope, etc.) However, noise abatement flight operations can be utilized in practice for terminal area approaches. For example, if BVI noise from the main rotor contributes to overall noise levels during descent, the SMRC could descend with wing flaps deployed, and the wing providing most of the total lift. In this configuration, the main rotor would be operating at very low thrust, substantially reducing potential BVI noise. Also, the required propulsive force would be lower, so although the propellers are operating at high tip speed, their loading would be lower than for climb and cruise. Similarly, while the CTR could use the gated nacelle angles, the pilot could also employ alternate nacelle angles and reduced rotor rpm during final approach to minimize noise in practice.

The risk of non-compliance for a transport tilt-rotor is considerably less as long as the maximum rotor tip speed is maintained at or below the 750 ft/sec design target.

The European Union has set aggressive goals to reduce helicopter noise. A European-funded research project called "Friendcopter" ([www.friendcopter.org](http://www.friendcopter.org)) initially set a goal of reducing helicopter noise levels to an average that is 10 dB below current limits established by international civil aviation authorities (i.e., ICAO, JAA, FAA). Their charter has recently stated that their goal is to reduce acoustic footprints by 30 to 50% depending on the flight condition. Some of this reduction will be achieved through noise abatement flight operations at heliports. This goal is an addition to reducing fuel consumption, vibration levels, and cabin noise.

### **11.3. Cabin Noise**

Cabin noise is not regulated by any civil aviation authority, and is only addressed by manufacturers as a potential marketing advantage, if cabin noise reduction technology is included in the aircraft design. Because of the potential for competitive advantage, cabin noise measurements are rarely published.

The cabin noise environments for helicopters and tilt rotors are inherently different. Tiltrotor cabin noise is dominated by rotor tones, whereas conventional helicopter cabin noise is primarily dominated by main gearbox noise, and, occasionally, ancillary devices such as cooling fans, compressors, or hydraulic pumps. In a compound helicopter configuration, there would be the additional noise produced by the propellers. While tilt rotors produce relatively low frequency discrete tones, compound helicopter cabin noise would contain both high frequency transmission noise and low frequency propeller noise.

The technical approach to minimizing cabin noise in helicopters is complex, and generally includes implementation of conventional noise reduction technologies, including mass barrier, isolation, absorption, and damping materials. Advanced active control technologies are difficult to apply in conventional helicopters due to the relatively high frequencies and correspondingly high number of acoustic modes within the cabin enclosure, as well as structural resonant modes within the airframe. Tilt rotors, on the other hand, offer a better platform for practical implementation of active and advanced passive structural acoustic control technology due to their low frequency, discrete tone characteristics. These same technologies could be used for controlling propeller noise in a compound helicopter as well.

For a compound helicopter, the highest cabin noise levels would likely occur during maximum rotor speed and maximum torque conditions, i.e. vertical takeoff and climb. As the aircraft transitions to forward flight, rotor speed and torque would be reduced as the main rotor propulsive requirement is off-

loaded to the thrusting propellers and lifting wing. The gearbox noise would then be abated, depending on the extent of RPM reduction. Still, cabin noise reduction would have to be addressed for the takeoff condition. An advanced gearbox design, such as a split-torque face gear transmission, could potentially be significantly quieter than current spiral bevel – planetary gear configurations.

The European "Friendcopter" program aims to reduce helicopter cabin noise levels to below 75 dBA, levels normally associated with commercial airliners. This is an aggressive goal for rotorcraft, requiring significant advanced technology integration to minimize the weight penalties associated with conventional cabin noise reduction treatments. Passenger acceptance of transport category rotorcraft will depend largely on cabin comfort and noise levels. Current state-of-the-art in cabin noise treatments on helicopters may not be sufficient or economical to achieve acceptable noise levels. Advanced technologies will have to be explored, including both active and passive structural acoustic controls, damping, isolation, and tuned absorbers. For helicopters, the primary source of cabin noise is typically the main rotor transmission. Potential source noise reduction of the main transmission should be examined. For large transport helicopters, a split-torque face gear configuration with planetary gear phasing, high gear tooth contact ratio, and optimized tooth profile modifications, all offer significant noise reduction benefits. Minimizing noise at the source reduces the need for vibro-acoustic structural treatments in the airframe.

While helicopter cabin noise is typically dominated by mid- to high-frequency discrete tones, tilt rotor aircraft cabin noise is primarily driven by low-frequency rotor tones, due to the close proximity of the rotor blade tips to the fuselage. This aircraft platform is more ideally suited for the application of active noise controls, and even the use of passive tuned vibration absorbers applied to the aircraft skin would offer significant cabin noise reduction potential.

#### **11.4. Low-Noise Rotorcraft Design Technologies**

The primary external noise correlating parameter for rotors is tip speed, especially the advancing blade tip speed for helicopters. This and other parameters, including number of blades, solidity, and disk loading, are also major factors in determining rotor performance. From an acoustics standpoint, an "efficient" rotor system is one that can produce the required lift at a relatively low tip speed, and therefore produce less noise. Any improvement in rotor aerodynamic efficiency can potentially be utilized in designing a quieter rotorcraft while maintaining the current level of performance, instead of using it exclusively to improve performance.

Increasing the number of blades tends to reduce the magnitude of the higher harmonics of rotational noise. Generally, 4- and 5-bladed rotors are quieter than 2- or 3-bladed rotor systems. This can be attributed to numerous factors, depending on the flight condition.

The blade tip planform and airfoil section can influence rotor noise by altering the tip aerodynamic loads and the structure of the tip trailing vortex. The airfoil section shape and thickness-to-chord ratio near the tip should be selected for good characteristics at high tip Mach number due to the importance of compressibility effects and tip vortex roll-up on noise. Properly selected tip geometry can significantly reduce blade-vortex interaction loads and the corresponding BVI noise.

For the SMRC, a multi-speed gearbox would permit optimized control of the rotational speeds of the propellers and the main rotor. Such a configuration could be used to optimize rotor speeds for minimum noise during terminal area operations.

Active control flaps embedded in the trailing edge of rotor blades have been demonstrated in full-scale testing to reduce blade-vortex interaction (BVI) noise in the NASA Ames 40x80 wind tunnel at Moffett Field, CA. BVI noise is a major contributor to terminal area noise, and is primarily generated during



approach descent operations. BVI noise reductions of up to 8 dB were observed in the wind tunnel. It is believed that further reductions, perhaps to 10 dB, can be achieved through optimization of the blade flap design.

Tilt rotors produce relatively low external noise in cruise mode due to their reduced rotor speed and torque requirements. Low noise technologies for tilt rotors should be aimed at reducing rotor noise for terminal area operations and low speed forward flight.

## **11.5. Noise Abatement Flight Operations**

Noise abatement of flight operations can be achieved in two ways. One is to establish optimized flight patterns that minimize noise exposure to the surrounding communities. The other is to actively manage airspeed, power settings, and transition scheduling to minimize source noise levels. For example, in the former case, aircraft can approach to land using a steep glide slope, thereby minimizing the approach-to-land noise footprint. In the latter case, tilt rotor aircraft could minimize their vertical lift operations near terminal areas. This would mean transitioning to cruise mode quickly after takeoff, and by delaying transition to vertical lift as much as possible during landing.

These noise abatement flight operations would have to be implemented while maintaining acceptable passenger comfort levels.

It has also been demonstrated in tests that helicopters can significantly reduce their acoustic footprint during approach descents by using a gradually decelerating airspeed throughout the descent. The deceleration effectively reduces the tip-path-plane angle-of-attack of the rotor with a corresponding reduction in BVI source noise.

## 12. Summary

Previous studies have determined that Simultaneous Non-Interfering (SNI) Operations at major airports could significantly increase passenger throughput, addressing the issue of serious overcrowding at major airports. This includes operate from existing airports to take advantage of that existing infrastructure and to support the role of short haul, without interfering with fixed-wing operations. Other important attributes of a successful civil transport rotorcraft are:

- It must be economically competitive in its operations, meaning the airframe should operate at high Lift/Drag ratio and have reduced fuel flow in cruise. It must also have low maintenance costs, high reliability, and high availability, even in the face of high utilization.
- It must be passenger friendly, requiring comfortable levels of cabin noise and relatively low cabin vibration, near turboprop levels.
- It must be community friendly, requiring low external noise on takeoff and approach.

Civil certification and community acceptance require lower external noise in the terminal area. The risk for CTR civil noise certification is judged to be low. The risk for SMRC civil noise certification is judged to be high for the baseline design, but low if a two-speed transmission is incorporated so the propellers operate at lower tip speed in hover and low speed flight.

Two baseline civil transport rotorcraft concepts were sized to notional civil transport missions to assess the benefits of advanced technologies; a Civil Tilt Rotor (CTR) and a Single Main Rotor Compound Helicopter (SMRC). The upper limit of each rotorcraft concept's competitive range was determined by where the rotorcraft block speed matched or fell below its primary competitor (aircraft with higher block speeds are more competitive). That criterion ensures the civil transport rotorcraft gate-to-gate time is less than the competition.

- The CTR with 300 to 350 knot cruise airspeeds was found to be competitive with turboprop and small turbofans over a 600 nm mission radius.
- The SMRC with a 250 knot cruise airspeed was competitive with turboprops over a 350 nm mission radius.

A broad survey identified over 120 potential advanced technologies. The categories of advanced technologies included advanced engines, reduced weight, improved airframe performance and rotor performance, flight controls, acoustics, and dynamics. The baseline designs were then resized using the most advantageous advanced technologies, first applied individually and then as a group, to determine improvements in the key performance parameters.

Several important technical areas, such as acoustics, health usage monitoring, and dynamics, did not directly contribute to the resizing and cost evaluations. However, effective application of advanced technology in these areas are essential to achieve community acceptance (external noise), passenger acceptance (comfort), and low maintenance costs.

Cost competitiveness depends on the scale of the rotorcraft (number of seats), operating cost / FH, and block speed, as captured in the metric of Cash Direct Operating Cost / Available Seat -NM (DOC/ASM). The cost of maintenance, fuel and oil, which the airframe manufacturer can influence, constitutes about 83% of Cash DOC/ASM.

The three categories of advanced technologies providing the greatest potential benefits to civil transport rotorcraft are summarized in Table 31, relative to the aircraft baseline empty weight (EW) and DOC/ASM.

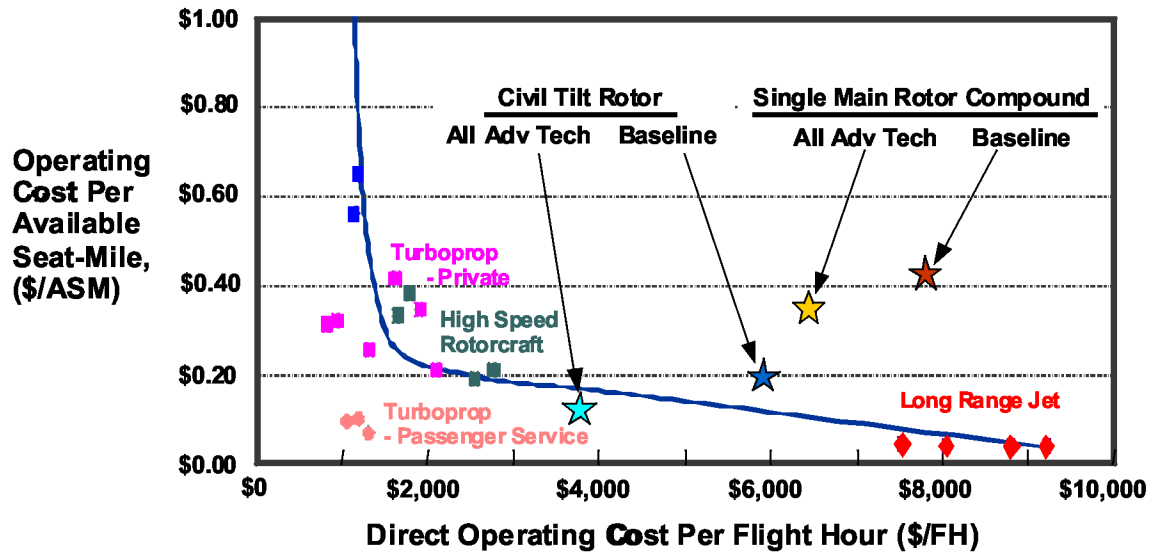
**Table 31. Net Benefit of Advanced Technology on Civil Rotorcraft Empty Weight and DOC/ASM**

	CTR		SMRC	
	EW	DOC/ASM	EW	DOC/ASM
<b>Reduced Engine SFC</b>	<b>97.4%</b>	<b>84.0%</b>	<b>97.9%</b>	<b>95.0%</b>
<b>All Weight Reductions</b>	<b>76.0%</b>	<b>86.3%</b>	<b>74.4%</b>	<b>92.3%</b>
<b>Drag + Download + Rotor Eff.</b>	<b>97.0%</b>	<b>85.2%</b>	<b>89.1%</b>	<b>90.9%</b>
<b>All Advanced Technology</b>	<b>70.0%</b>	<b>61.1%</b>	<b>68.0%</b>	<b>82.3%</b>

The quantitative evaluation of advanced technologies to rotorcraft concepts showed that:

1. Advanced turboshaft engines with reduced fuel flow and increased HP/weight ratio offered the most benefit to down-size the rotor and wing of future rotorcraft, to reduce the mission fuel, and to reduce the operating cost metric of DOC/ASM. Advanced engines with an estimated 20% reduction in fuel flow over the next 15-20 years gave a 16% reduction in DOC/ASM for the CTR, assuming a fuel cost of \$5 per gallon.
2. Structural and drive system weight reduction were the second most beneficial advanced technologies, for both concepts. The overall reduction in SMRC structural weight gave a 8.4% reduction in empty weight and a 2.5% reduction in DOC/ASM. Comparable values for the CTR were 12% and 6.8%, respectively. Reduced drive system weight from advanced technology gave 9.5% less empty weight and 2.7% lower DOC/ASM for the SMRC, with 6.7% and 3.5% respectively for the CTR. Weight reductions from all advanced technologies lowered CTR empty weight by 24% and DOC/ASM by 13.7%.
3. Parasite drag reduction was the third most beneficial technical area. It reduced the CTR DOC/ASM by 10% and the SMRC DOC/ASM by 6%.
4. Advanced technologies and designs that improve rotor performance and reduce aircraft drag have significant payoff for mission fuel and weight empty. The combined benefit of advanced performance technologies (excluding advanced engine technology) gave a 3% reduction in CTR empty weight and 15% lower DOC/ASM. Advanced performance technologies gave the SMRC 11% lower empty weight and 9% lower DOC/ASM.
5. The advanced technologies can be expected to provide similar relative benefits to standard helicopters, where fuel is a large part of their operating cost

Applying all the selected advanced technologies gave significantly lower operating costs, measured by DOC/FH and DOC/ASM. Figure 92 contrasts the baseline CTR and the SMRC values of DOC/ASM to that with all advanced technologies. The DOC/ASM of the advanced SMRC is economically competitive with private turboprop operating costs, and the DOC/ASM of the advanced CTR is on economic parity with turboprop passenger service.



**Figure 92. Effect of All Advanced Technologies on the CTR and SMRC Rotorcraft**

Promising technologies identified in this report should be high on the NASA SRW list for development funding to maturity TRL level 6. The priority determined by this study is: 1) advanced engine technology, 2) structural and drive system weight reduction, and 3) rotor performance and airframe drag reduction.

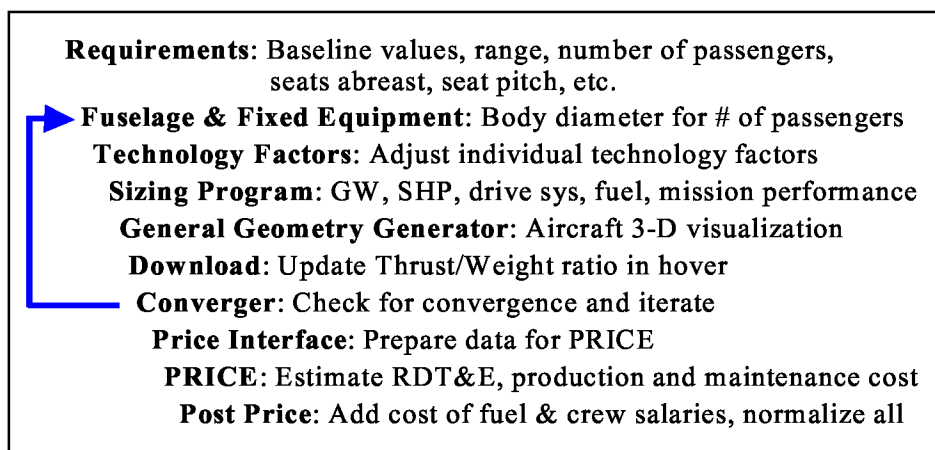
## 13. Appendices

### Appendix A. RCDA

Integrating modules from other disciplines with the legacy sizing code enhances the fidelity and utility of the conceptual sizing, providing immediate assessment of air vehicle characteristics that are not part of the legacy sizing code. A consequence of an integrated MDA analysis has led to a better understanding of the interaction between technical disciplines.

Modules must be sequenced by the logical order of the data flow, beginning with Requirements. An initial vehicle sizing is performed, which may be preceded by or followed by other modules providing supplemental analysis needed for the exercise. Additional modules usually require additional input data for their function. The iterative nature of aircraft sizing required application of the ModelCenter Converger tool. The rotorcraft sizing was iterated to convergence, followed by the PRICE module to estimate costs.

The modules in *RCDA* can be tailored to satisfy the design goals. The *RCDA* model is shown schematically in Figure 93. The Fuselage & Fixed Equipment module sizes the body diameter and length based on the input number of passengers, seat pitch, seats abreast, and aisle width. This was a significant module in the early stages of the NASA civil rotorcraft study, allowing automatic scaling of both fuselage size and fixed equipment weight with parametric changes to the number of passengers. For example, the weight of furnishings depends on the number of seats, floor area to be carpeted, and coverings for sidewall area. More passengers and larger cabin space also change the demand on the environmental control system (ECS) for pressurization, heating and cooling.



**Figure 93. RCDA Modules And Sequence**

The General Geometry Generator (GGG) provides visibility of the overall aircraft and fuselage contours. It calculates total body wetted area that is used by the sizing program in succeeding iterations. It may also generate fuselage cross-section data at multiple stations. That data flows down to the hover Download module, which provides an updated hover T/W based on the revised geometry. The updated hover T/W ratio is used when the aircraft is resized in the succeeding iteration. The data-driven sequence is relatively obvious at this stage of conceptual design.

Both the Single Main Rotor Compound helicopter configuration and the Civil Tilt Rotor configuration required new GGG modules for their respective unique geometries. These GGG modules were developed under Boeing funding as generic rotorcraft types. New hover download modules were also developed for

the CTR and the SMRC compound configuration. Both the fuselage and the wing contribute to the SMRC hover download.

Sizing and performance analysis of the Civil Tilt Rotor is performed by *RCDA-TR*, using the legacy VASCOMP program. Sizing and performance analysis of the SMRC is performed by *RCDA-SR* using the legacy HESCOMP program, with its built-in options for compound helicopters. Supplemental modules in these *RCDA* models included the following.

### **Fuselage and Fixed Equipment Module**

This module calculates fuselage diameter and length, with inputs for number of passenger seats, seats abreast, seat pitch, seat width, and aisle width. The cabin size also accounted for galley area, closet and baggage areas on the cabin level, as the small 3 and 4 abreast cross-sections of these rotorcraft did not allow for baggage below the main deck. This module also scales the weight of fixed equipment to the number of passengers, and provides a breakdown of fixed equipment component weights for the PRICE cost model. Fixed equipment weight includes the APU, Instruments, Electrical, Hydraulic, Avionics, ECS, Ice Protection, Load & Handling, and Furnishings & Equipment. The number of passengers was used in this module to scale fixed equipment weight as a surrogate for aircraft size. Other calculations provide data such as maximum operating Mach number, maximum operating airspeed (KEAS), and dive speed (KEAS) to VASCOMP and HESCOMP, based on inputs for the design cruise speed and altitude. A fuselage weight penalty for pressurization was calculated as a function of the cruise altitude and used by the sizing program to more accurately reflect the consequence of higher cruise altitudes. These simple pre-calculations provide automated input to HESCOMP and VASCOMP, allowing parametric exploration to determine the best combination of cruise condition and wing loading.

### **GGG Module**

A GGG module was tailored to each concept, the CTR and the SMRC. While these displayed relatively simple geometry, they served the function of visualizing the locations and relative size of aircraft components. It was especially beneficial for the new SMRC concept, to see potential intersections of the main rotor and the propellers.

### **Download Module**

Tilt rotor download/thrust is fundamentally a function of the ratio of wing chord-to-rotor diameter and the effective wing drag coefficient, accounting for reduced chord of deflected flaps in the hover mode. The relationship was derived by Boeing Senior Technical Fellow, Anthony McVeigh, correlated to the current V-22 download, and coded in Excel. Incremental adjustments can be added to account for future advanced technology, such as Active Flow Control (AFC) devices.

Hover thrust/weight ratio used in HESCOMP and VASCOMP =  $1 / (1 - \text{Download/Thrust})$

Download of the SMRC derives from both the fuselage and the wing, as both are exposed to the rotor downwash. HESCOMP has a built-in allowance for the fuselage download. A supplemental calculation was developed for the wing contribution to download. This was different from the tilt rotor downwash module because the single main rotor flow field and downwash distribution are quite different from the two, higher disk loading rotors on a tilt rotor.

## **Technology Factor Module**

The technology factor module was a convenient means of selecting which advanced technologies would be applied during a sizing case. It was populated with factors for advanced technologies from structures, performance, rotor and drive systems, and engine fuel consumption. This allowed the selection of one technology, one group, or combinations.

## **Price Interface Module**

This module expanded component weights from HESCOMP or VASCOMP into the elements required by the PRICE programs WBS structure. The WBS breakdown was consistent with previous PRICE models for Boeing products, thereby applying previous cost estimating experience and calibrations for the two rotorcraft concepts evaluated in this study. The PRICE model for the SMRC began with a helicopter model, adding the wing, propellers, and extra drive system parts.

VASCOMP and HESCOMP apply calibrated weight trend relationships to estimate the weight of the drive system, the rotor, the wing, the engine, the empennage, and the fuselage. Other VASCOMP weight groups include the Flight Control System and an input value for Fixed Equipment and Fixed Useful Load. For example, VASCOMP provides a single value for the drive system weight, but the CTR PRICE model required that be split into these components;

- Prop rotor Gearbox (Ship Set)
- Drive System Purchased Equipment
- Tilt Axis Gearbox (Ship Set)
- Midwing Gearbox (Ship Set)
- Interconnect Shafting
- Emergency Lubrication System

Similarly, the single value for wing weight was split into these components for PRICE;

- Wing torque box
- Wing Purchased Equipment
- Pylon Downstop & Support
- Flaperon Fairings (Ship Set)
- Integration Equipment

The components of Fixed Equipment were calculated in the Fuselage and Fixed Equipment Module based on number of passengers. Each of these were further broken down in this Price Interface module to comply with the existing WBS.

The completed breakdown and output to PRICE had over 85 distinct values. This would not be a practical approach if data did not already exist to support cost estimates for 85 elements. It was practical for this study in two respects: Boeing had the product data to support this WBS, and Boeing's cost estimating team had existing cost models based on those breakdowns.

## **PRICE Module**

The PRICE module provided an estimate of development cost, production cost, and maintenance costs. The assumptions and ground rules are given in section 5, and a brief description of the PRICE model is given in section 4.3.

## **Post-PRICE Module**

Development cost, production cost and maintenance costs were estimated by the PRICE program. But the desired metric was Cash Direct Operating Cost per Available Seat-NM, or Cash DOC/ASM, described in section 5.2. Cash DOC/ASM requires several additional, significant components for Operating and Support (O&S) cost, such as the cost of fuel. The Post-PRICE module calculates the additional needed components and adds them to the maintenance cost from PRICE to develop Cash DOC/ASM.

This module also normalizes the output cost data to that of the Baseline aircraft, providing relative costs, which are used to quantify the benefit of advanced technologies. All costs, Development Cost, Production Cost, and O&S Cost are normalized and output as relative values. The relative Cash DOC/ASM is used to compare the benefit of advanced technologies, but absolute values are used to compare back to existing turboprop data.

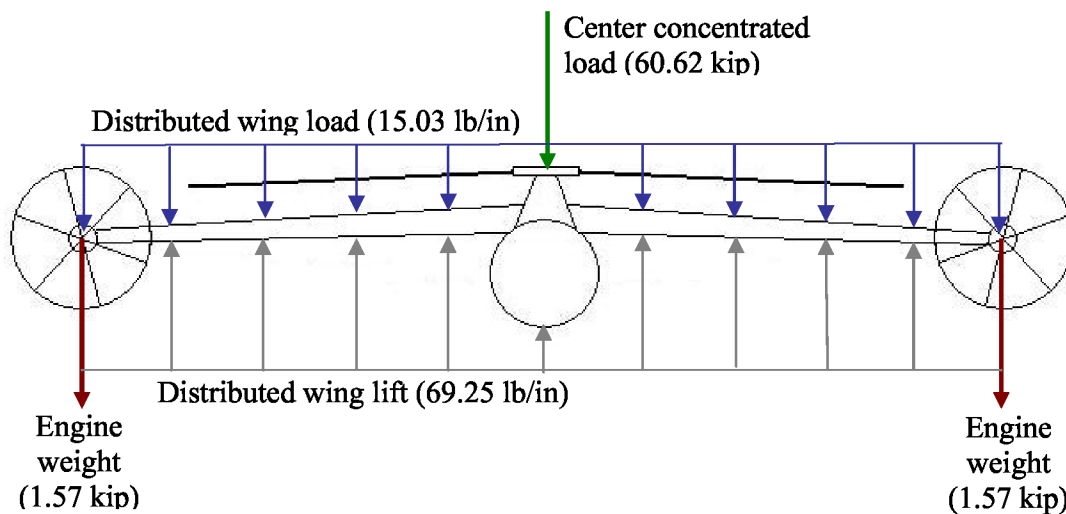


## Appendix B. Structural Analysis for the SMRC Helicopter Concept

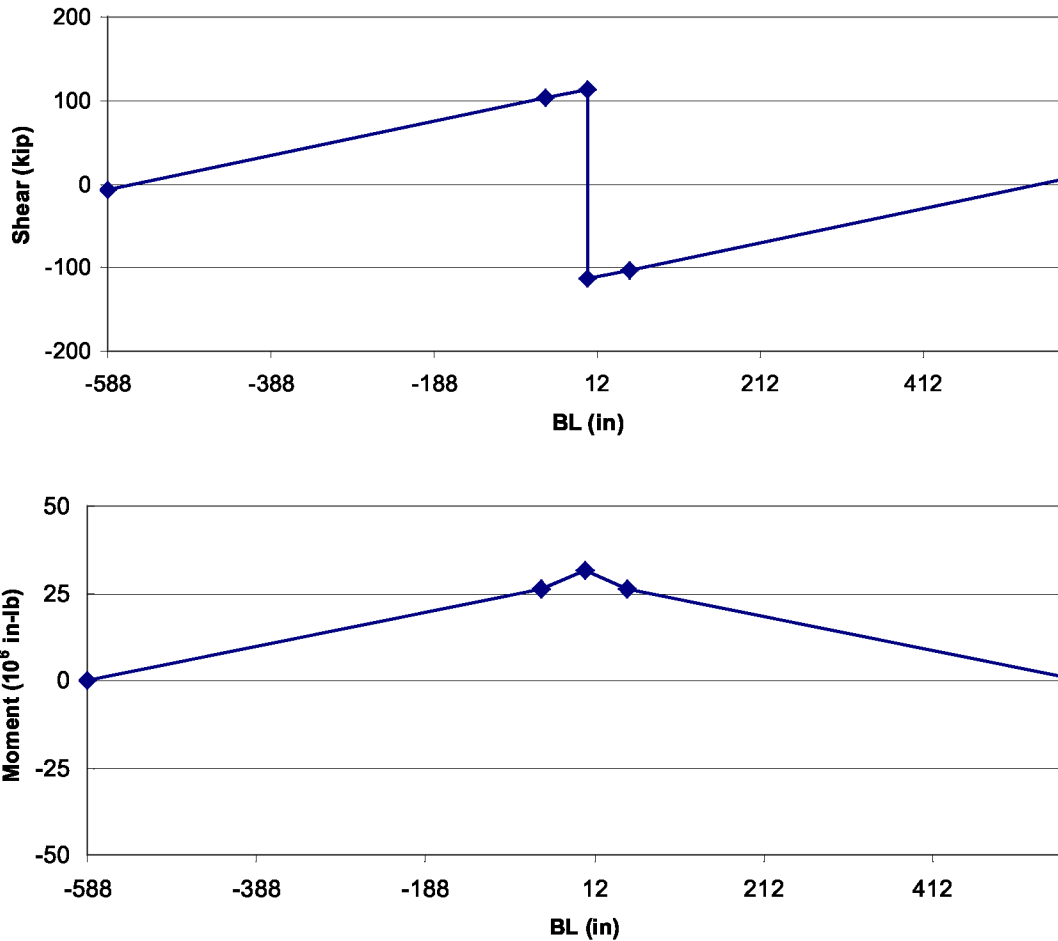
A preliminary analysis of the primary structure was conducted on the SMRC helicopter concept design to determine the feasibility and potential weight savings of applying tape laminate and core to the primary structure of the aircraft. This analysis was not intended to establish structural adequacy.

The following design details and assumptions apply to the SMRC helicopter and analysis:

- The wing is positioned over the fuselage
- The wing crosses the fuselage at mid ship
- The flight loads are carried by the wing
- Typical material properties and allowables for carbon tape and core are applicable
- Ultimate loads are based on a factor of safety of 1.5 and 2.5g flight condition
- Source of weight / dimensional information: Reference 1 (see page 5)



The following diagrams show the shear and moment distributions across the wing that were used for ultimate loads. Ultimate loads are used to complete the analysis.



### Fuselage and Frames:

The fuselage skin was analyzed for pressure loading and fuselage bending. For pressure loading, it was assumed that the internal pressurization level would be equivalent to 7,000 feet (11.4 psi) and that the maximum flight altitude would be 30,000 feet (4.4 psi) resulting in a pressure load of 7.0 psi. A factor of safety of 2.0 was included in the pressure loading calculations. The maximum fuselage bending moment ( $4.75 \times 10^7$  in-lb) was calculated at mid ship:

$$Moment = \frac{(Gw/FL) \cdot FL^2}{8} \cdot 1.5SF \cdot 2.5g \quad Gw = \text{gross weight (lb)}, FL = \text{fuselage length (in)}$$

Based on the minimum required skin thickness for pressure loading (90°-fiber direction) and fuselage bending (0°-fiber direction), a proposed distribution of ply count was developed including +/- 45° plies. Additionally, 1.0 inch core provides local stability to the skin as well as thermal and acoustic insulation. The total weight of the fuselage skin is 3537 lb. The details supporting this result are tabulated below.

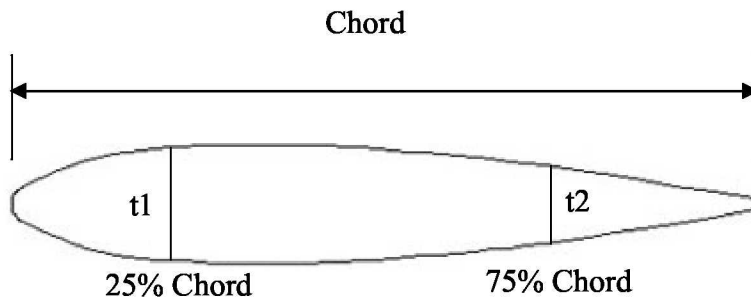
Station (in)->	0 to 200	200 to 900	900 to 1100	1100 to 1243
Ply Count / Facesheet	6	9	8	7
Carbon Thickness (in)	0.089	0.133	0.118	0.104
Core Thickness (in)	1.00	1.00	1.00	1.00
Total Thickness (in)	1.09	1.13	1.12	1.10
Weight Carbon (lb)	324	1701	432	271
Weight Core (lb)	130	456	130	93
Weight (lb)	454	2157	562	364
Total Weight (lb)				3537

Analysis was completed to estimate the weight of the frames. A pitch of 24 inches is assumed between frames. The frames were sized so that one frame could carry the hoop load if the skin and frames across two frame bays failed. The number of plies required to make the area of one frame equivalent to the area across two bays based on the required hoop thickness was determined. It was assumed that the frames have a “c” shaped cross section with the major dimensions of 4 x 1 inches. The total weight of the frames is 286 lb assuming that there are 45 frames.

Thickness of frame required (in)	0.056
Resulting no. of plies	8.0
Weight of 1 frame (lb)	6.4
Total weight 45 frames (lb)	286

#### Wing Box:

To simplify analysis it was assumed that the shape of the wing box is rectangular, and the thickness is an average value based on the given geometry. It was also assumed that the thickness-to-chord ratio was constant for the length of the wing. The dimensions of the wing box at the root and tip were then determined as follows:



Given dimensions:  
 $t/c = 0.18$   
 Chord @ root = 166.2 in  
 Chord @ tip = 10.8 in  
 Resulting geometry  
 (base x height):  
 Root – 83 in x 25 in  
 Tip – 30 in x 9 in

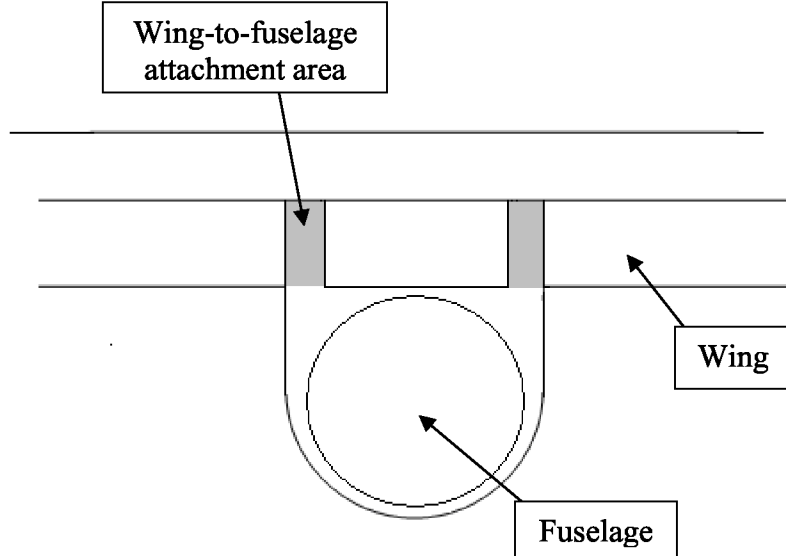
The wing box was analyzed to determine the minimum required thickness for bending and stability of the cap and web. The shear and moment at the wing-to-fuselage joint and wing tip were used in the analysis (in accordance with the shear and moment diagrams). Based on the minimum required thickness of the cap and web and the force distribution across the wing, a proposed distribution of ply count was determined. The total weight of the wing primary structure is 2502 lb.

Wing Box Cap	BL (in)->	0 to 52	52 to 152	152 to 252	252 to 352	352 to 452	452 to 552	552 to 588
Ply Count / Facesheet		24	20	16	12	8	8	8
Carbon Thickness (in)		0.355	0.296	0.237	0.178	0.118	0.118	0.118
Core Thickness (in)		1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total Thickness (in)		1.855	1.796	1.737	1.678	1.618	1.618	1.618
Weight Carbon (lb)		85.6	129.4	90.4	58.0	32.1	25.5	7.6
Weight Core (lb)		12.9	23.4	20.5	17.5	14.5	11.6	3.4
Weight Sandwich (lb)			152.8	110.9	75.5	46.6	37.1	11.1
Total Weight per Cap (lb)								532

Wing Box Web	BL (in)->	0 to 52	52 to 152	152 to 252		352 to 452	452 to 552	552 to 588
Ply Count / Facesheet		16	12	8	8	8	8	8
Carbon Thickness (in)		0.237	0.178	0.118	0.118	0.118	0.118	0.118
Core Thickness (in)		0.38	0.38	0.38	0.38	0.38	0.38	0.38
Total Thickness (in)			0.553		0.493	0.493	0.493	0.493
Weight Carbon (lb)		17.2	23.4	13.6	11.6	9.7	7.7	2.3
Weight Core (lb)		1.0	1.8	1.5	1.3	1.1	0.9	0.3
Weight Sandwich (lb)		18.2	25.1	15.1	12.9	10.7	8.5	2.5
Total Weight per Web (lb)								93

### Wing-to-Fuselage Joint:

To determine the feasibility of joining the wing design to the fuselage the number of fasteners required was determined. Based on the web geometry, assumed fastener diameter of 0.375 in, and the assumed allowable bearing stress the number of fasteners required is 20 due to a shear force of 103 kip. With a web height of 24 inches and fastener spacing of 4D, there could be a maximum of 15 fasteners in one row. Therefore, only 2 rows of fasteners would be required.



### Summary:

Results from the structural analysis of the fuselage and wing box primary structure are tabulated below.

Fuselage			Wing Box		
Skin Weight	(lb)	3537	Cap Weight	(lb)	2130
Frame Weight	(lb)	286	Web Weight	(lb)	373
Total Weight	(lb)	3823	Total Weight	(lb)	2502

Preliminary weight estimates were provided based on HESCOMP (Helicopter Sizing and Performance Computer Program) analysis for comparison. The preceding analysis for the primary structure is assumed to account for 50% of the fuselage structural weight, and 40% of the wing structural weight. These percentages were applied to the HESCOMP estimate to determine the target weight for comparison. Components that were not included in the fuselage and wing weight estimates from this analysis include all secondary structure and other components, listed below.

#### Fuselage

- Bulkhead
- Cargo floor
- Passenger floor
- Passenger area
- Cockpit structure
- Wing integration
- Empennage

#### Wing

- Ribs (x4) for wet wing
- Intermediate ribs
- Engine integration
- Rotor integration
- Leading edge
- Trailing edge
- Drive shaft support structure
- Flight controls support
- Systems support
- Fuel sealing

The analysis shows the potential for weight savings and feasibility of design by applying laminate and core technology to the primary structure of the aircraft. The analysis is meant to serve as an indicator for the potential of such methods, and not to establish specific design criteria or structural adequacy.

Structure	HESCOMP Prediction* (lb)	Target %	Target (lb)	Estimate (lb)	Savings
Fuselage	9522	50%	4761	3823	20%
Wing	7857	40%	3143	2502	20%

## Appendix C. Effect Of Advanced Technologies On The SMRC

The following charts provide a more complete picture of advanced technologies on SMRC empty weight, mission fuel, gross weight, development cost, production cost, DOC/ASM, and DOC/FH.

